XX CONGRESO GEOLÓGICO INTERNACIONAL

SYMPOSIUM SOBRE YACIMIENTOS DE PETROLEO Y GAS

EDITADO POR

EDUARDO J. GUZMÁN

TOMO II

ASIA Y OCEANIA

MÉXICO

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Geology

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CONTENIDO

TOMO II

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SYMPOSIUM SOBRE YACIMIENTOS DE PETROLEO Y GAS
XX CONGRESO GEOLOGICO INTERNACIONAL

ASIA

SAUDI ARABIA
(ARABIA SAUDITA)

GEOLOGY AND OIL RESOURCES OF EASTERN SAUDI ARABIA *

By W. H. Thralls ** and R. C. Hasson **

ABSTRACT

The central part of the Arabian Peninsula (Interior Homocline) is characterized by an arcuate belt of exposures of a relatively complete sequence of late Paleozoic and Mesozoic rocks which dips generally eastward at an almost uniform low rate from the basement area of the west to Hasa Structural Terrace in northeast Arabia. This terrace is structurally almost flat with undulations of low relief but with several generally north-south trending major anticlines rising above the general level. All producing fields are located within Hasa Structural Terrace with the bulk of the production coming from these major anticlinal axes (En Nala, Abqaiq-Qatif) which probably owe their origin to movements of fault blocks in the underlying basement. Eocene and younger Tertiary rocks cover this region.

After disappointing results from several Middle Cretaceous wells on Damman Dome, the first worth-while commercial production was encountered there in the Upper Jurassic in March, 1938. Following the discovery of Abqaiq (1940) exploration lagged due to the international situation. After the war it was resumed with surface mapping, gravity-magnetic and seismic surveys and structure drilling. In 1955 production reached a new high daily average of 965,041 barrels with cumulative production through the years in excess of 2.3 billions of barrels.

INTRODUCTION

This paper is a compilation of opinions derived from published articles by geologists of Arabian American Oil Company. Subject matter is principally confined to the producing area. Between the

* Published by permission of Arabian American Oil Company.
** Arabian American Oil Company (Aramco), New York, New York.

escarpments of central Arabia, where excellent exposures of late Paleozoic and Mesozoic rocks may be studied, and the area of oil search in northeast Arabia lies a vast region in which few shallow holes and practically no deep ones have been drilled. It is known that lithofacies changes take place within this interval. Truncation of older rocks on a regional scale is known tô take place at rates of a fraction of a meter per kilometer. Some half-dozen unconformities of this regional type are known. This much general knowledge has been pieced together from widely distributed observations. Details are lacking, therefore any all-inclusive discussion or regional geology at this time would have many weaknesses and is beyond the scope of this paper.

Negotiations with the Saudi Arabian Government for a concession in eastern Saudi Arabia were completed in May 1933. Methods of exploration and development of the presently productive areas are chronicled in the text proper beginning with the first commercial production obtained from Damman Dome in March 1938. More important events occurring during this five-year interval include the beginning of systematic field mapping in October 1933 of which the first step was the detailing of Damman Dome. During the 1933-34 field season, reconnaissance surveys of more than 90,000 square kilometers where completed with no other such obvious structure as Dammam being found. In 1934 and 1935 study of the coastal Miocene stratigraphy was intensified, and studies of the ground waters of the region initiated. By summer of 1935 Dammam Well 1 had been 'spudded', surface indications of Abqaiq and Qatif had been found, the En Nala area west of Hofuf was known to be regionally high and El Alat had been mapped by the plane table method. During this same 1934-35 season, surface work was carried north and west toward basement exposures, and outcrop sections were measured in order to set up a stratigraphic section to guide wildcat drilling in the coastal area. Structure drilling early became an important method of exploration.

The first contract seismograph party arrived in Arabia in the early part of 1937. By this time most of the rock units were recognized and named by the late Max Steineke * in unpublished writings. The year 1938 was a decisive one in Company operations. Ten wells on Dammam Dome had been bottomed in the Middle Cretaceous pro-

* Formerly Chief Geologist, ARAMCO, and Sidney Powers Memorial Medalist, 1951.

ductive zone of nearby Bahrain Island with disappointing results. Dammam Well 7, drilled to explore lower horizons, found oil in commercial quantities in the late Upper Jurassic 'Arab' formation in March 1938.

PHYSIOGRAPHIC PROVINCES

Six physiographic provinces (Fig. I), the boundaries of which follow quite closely the outcrop pattern of Saudi Arabian geology, are described below.

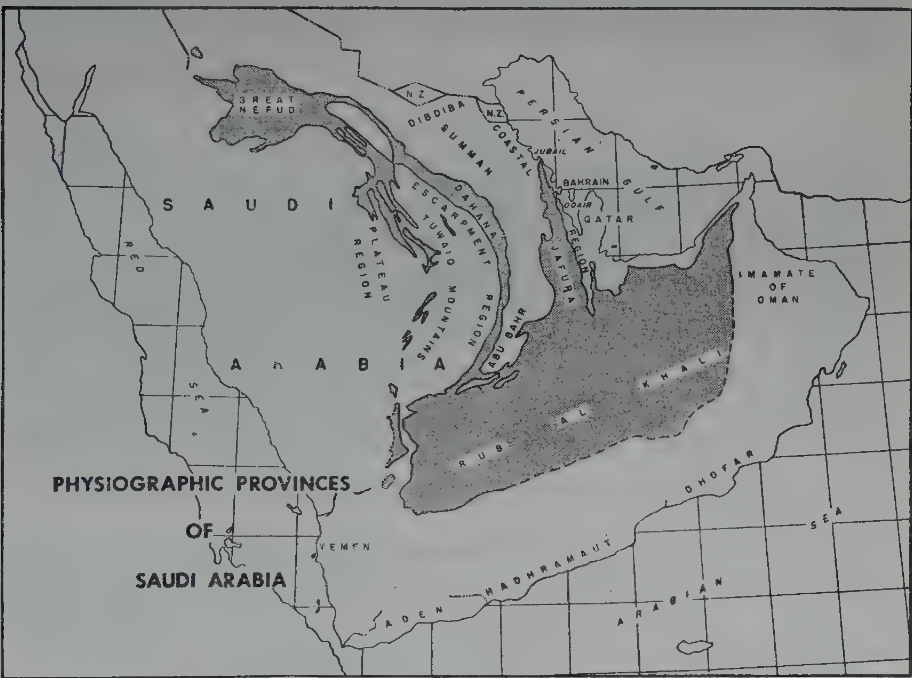

FIGURE I

Central Plateau

The Central Plateau is an outcrop area of pre-Cambrian crystalline basement rocks of the ancient stable mass of the African-Arabian shield. Elevations range from 800 to 1800 meters.

West Facing Escarpments

East of the Central Plateau region and in a great arc around it is a series of west facing escarpments, some with as much as 500 meters relief, with long dip slopes to the east. The scarps are outcrops of predominantly Mesozoic rocks separated from the Central Plateau by a relatively narrow band of Paleozoic (Cambrian to Devonian, Permian). The arc is some 1500 kilometers in length and 320 kilometers wide extending from the south end of the Tuwaiq Mountains to the Great Nefud on the north. The topographically low area between the Tuwaiq Mountains scarp and the Central Plateau region to the west contains some of the larger nefuds (sand areas) of Arabia.

Dahana

East of the escarpment region is a great sand strip 25 to 75 kilometers wide extending from the Rub'al Khali on the south to the Great Nefud on the north, a distance of 1500 kilometers. The sand follows Eocene outcrops to 27° north latitude where it turns westward to join the Great Nefud. In the north, the sands are generally stabilized with limestone and dikaka (hummocky sand with sparse covering of small bushes and bunch grass) surfaces common. In the south, there are bands of active sand on each side of the Dahana in which moving dunes are common. Average elevation is 450 meters.

Summan Plateau

The Summan is a dissected limestone plateau of Miocene-Pliocene rocks varying in width from 80 to 250 kilometers. The plateau grades north into a vast, almost featureless gravel plain, the Dibdiba, and south into another gravel plain, the Abu Bahr, which in turn loses its identify under the sands of the Rub' al Khali. The eastern margin of the Summan is a sinuous line of east facing scarps. Average elevation is approximately 250 meters.

Persian Gulf Coastal Region

Southward from the border of the Kuwait-Saudi Arabia Neutral Zone the terrain is more or less stabilized low rolling sand ridges cov-

ered with dikaka inland and of sabkhas (salt flats) near the coastline. In the vicinity of Jubail and southward is a 30 to 120 kilometer wide belt of active sand dunes resting on salt flats. Sout of Oqair to the base of the Qatar Peninsula is an east facing escarpment. Between this escarpment and the Summan on the west a sand belt, the Jafura, extends from Jubail south to merge into the Rub' al Khali. Excepting small Eocene exposures at Dammam and Abqaiq, outcrops are Miocene-Pliocene in age. Highest elevations in the coastal region are seldom over 100 meters. The shoreline of the Persian Gulf is irregular with many sands spits. Shoals and occasional small coral reefs are common in shallow water which extends for a considerable distance into the gulf.

Great Sand Areas

The two great sand areas of Saudi Arabia are the Great Nefud and the Rub' al Khali. The Great Nefud covers an area of approximately 145,000 square kilometers in the northwestern part of the country. Along the western and southern margins, dunes are very high and almost conical in shape. The Rub' al Khali, one of the largest continental sand bodies in the world, covers an area approximately 1200 kilometers long and 650 kilometers wide. The central and western portions consists of regions of large undulations of rolling sand with occasional areas of dune sand. The eastern portion contains far more dune sand, the dunes becoming larger and more abundant eastward into the 'sand mountain' area. The 'sand mountains' are great dune ridges up to 20 kilometers in length and 300 meters in height.

STRATIGRAPHY

Pre-Permian

These Paleozoic rocks are sandstones, micaceous siltstones, and shales. Table 1, Figure II, Figure III. In spite of the large thickness of the beds involved, only a minor amount are shale, and most of this does not appear to have been strongly organic. The one unit which does include appreciable amounts of organogenic sediments (limestones) is the Jauf formation (Silurian and Lower Devonian). Available information indicates that the Jauf formations is restricted to an area bordering the northwestern edge of the Great Nefud.

TABLE I

SAUDI ARABIAN ROCK UNITS

ROCK UNITS	MAIN ROCK TYPES	THICKNESS (TYPE SECTION)	AGE
Hofuf formation	Sandy marl and limestone; local quartz gravel at base	95m	Miocene or Pliocene
Dam formation	Shale, marl and limestone, with chert	90m	Probably Middle Miocene
Hadrukh formation	Sandstone, shale, marl & chert	84m	?Miocene
Unconformity			
Dammam formation	Limestone, dolomite, clay and marl	28m	Lower and Middle Eocene
Rus formation	Anhydrite, marl, shale and limestone	56m	Lower Eocene
Umm er Radhuma formation	Mainly limestone and dolomite	About 217m	Paleocene and Lower Eocene
Aruma formation	Limestone, with dolomite and shale	144m	Late Upper Cretaceous (Campanian? and Maestrichtian)
Unconformity			
Wasia formation	Sandstone and shale with subordinate limestone	42m	Early Upper Cretaceous (Cenomanian)
Unconformity			
Biyadh sandstone	Sandstone, with shale	About 270m	Lower Cretaceous (Aptian - Albian)
Buwaib formation	Limestone, with subordinate shale and sandstone	34m	Late Lower Cretaceous (Probably Aptian)
Unconformity			
Yamama formation	Calcarenite and fine-grained limestone	58m	Lower Cretaceous (Probably Neocomian)
Sulaiy limestone	Limestone, with a basal calcarenite unit	About 180m	Probably Lower Cretaceous (?Neocomian)
Disconformity			
Riyadh group			
Hith anhydrite	Anhydrite	71m	Probably Upper Jurassic
Arab formation	Limestone, dolomite and anhydrite	127m	Late Upper Jurassic
Jubaila limestone	Limestone	About 100m	Upper Jurassic (Kimeridgian)
Hanifa formation	Limestone	101m	Upper Jurassic (?Oxfordian)
Tuwaiq Mountain Limestone	Limestone, mainly coral-bearing	215m	Upper Jurassic (Callovian)
Unconformity			
Dhruma formation	Limestone, and shale	383m	Middle Jurassic (Bajocian - Bathonian)
Marrat formation	Limestone, dolomite and red shale	111m	Lower Jurassic (Toarcian)
Unconformity			
Minjur sandstone	Sandstone, with varicolored shale	315m	Triassic or Jurassic
Jilh formation	Sandstone, shale and limestone	About 326m	Middle Triassic
Sudair shale	Mainly red shale	116m	Permian or Triassic
Khuff limestone	Limestone, with shale and marl	235m	Permian (Probably Upper)
Unconformity			
Jauf formation	Limestone and shale	276m	Silurian and Lower Devonian
Tawil sandstone	Sandstone	Over 200m	Silurian
Tabuk formation	Sandstone and shale	About 725m	Ordovician and Silurian
Saq sandstone	Sandstone	Over 600m	Presumably Cambrian
Unconformity			
Basement complex			

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Permian-Triassic

The Permian is represented in outcrop by the Khuff formation (probably Upper Permian) and possibly the overlying Sudair shale (Permian or Triassic). The Khuff consists of alternating chalky and dense limestones commonly with thin, hard shelly limestone layers In some places it is considerably dolomitized. Cream-colored marls and red and green gypsiferous clays occur in moderate amounts in the upper half of the unit and sporadically in thin beds through the

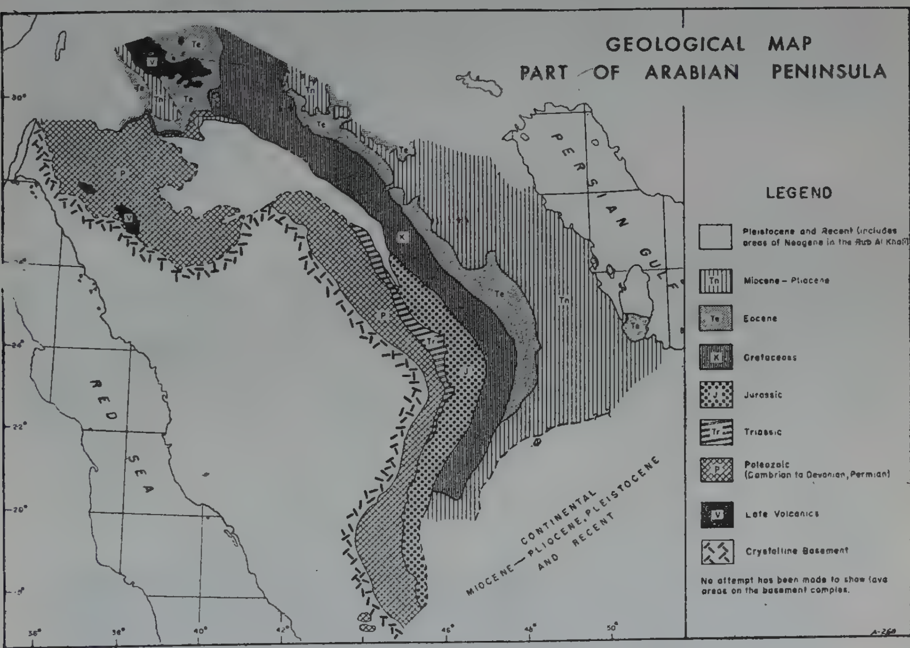

FIGURE II

remainder. In the coastal section the Khuff is probably shallow water limestone deposits with some intercalated thin beds of anhydrite. Evidence of gas has been encountered in the Khuff in coastal wells.

The Triassic in outcrop is predominantly sandstone with minor amounts of red to green shales and impure limestones. The underlying Sudair shale and overlying Minjur sandstone, here placed in the Triassic, are poorly dated and may possibly be Permian and Juras-

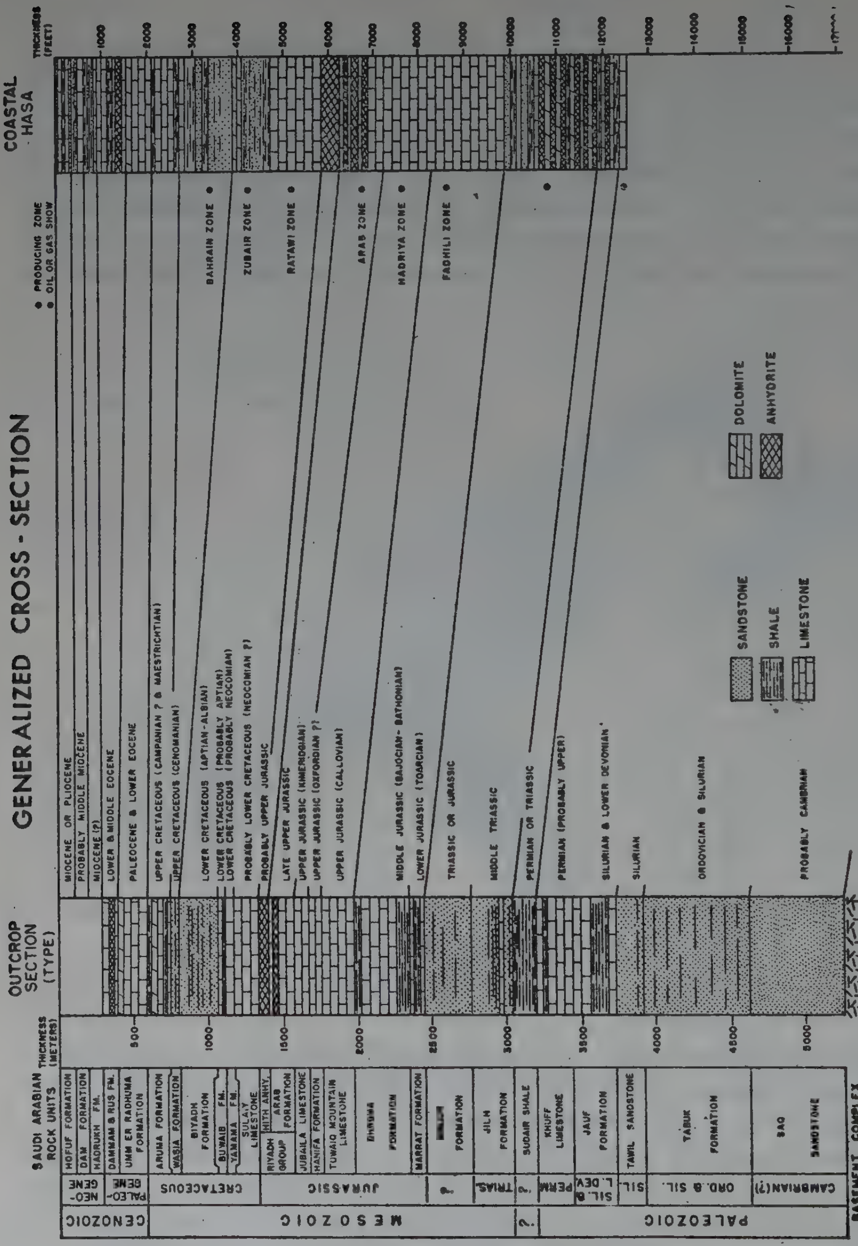
GENERALIZED CROSS - SECTION
OUTCROP SECTION (TYPE)
COASTAL HASA
SAUDI ARABIAN ROCK UNITS
THICKNESS (METERS)
THICKNESS (FEET)
PRODUCING ZONE
OIL OR GAS SHOW
BAHRAIN ZONE
ZUBAIR ZONE
RATAWI ZONE
ARAB ZONE
HADRIYA ZONE
FADHILI ZONE
SANDSTONE
SHALE
LIMESTONE
DOLOMITE
ANHYDRITE
CENOZOIC
MESOZOIC
PALEOZOIC
BASEMENT COMPLEX

FIGURE III

sic respectively. The coastal Hasa section assigned to the Triassic is composed of a lower unit of limestone, anhydrite and red and green shales, a middle dolomite-anhydrite series and an upper shale-sandstone unit. Oil shows have been encountered in the dolomite-anhydrite series.

Jurassic

The Lower Jurassic is represented in outcrop by the Marrat formation (Toarcian) which in its typical development consists of upper and lower limestone-dolomite units separated by a red shale member which is locally interbedded with sandstone. In the coastal area the Marrat has not been distinguished because of the lack of paleontological evidence, but its equivalent is probably a dark, dense, argillaceous limestone which separates dated Middle Jurassic rocks above and the underlying presumed Triassic.

At the outcrop the Middle Jurassic Dhruma formation (Bajocian-Bathonian) is in a shallow water facies and is composed primarily of limestone, with shale in the upper and lower parts. Clean current-washed calcarenites occur as thin members at various levels. In the coastal area fine-grained limestones, often dense and sometimes dark and argillaceous, dominate but variable proportions of fine calcarenite, usually with a fine lime mud matrix, are interbedded. The oil of the Fadhili field is found in a persistent fine calcarenite a short distance below the top of the Dhruma.

Rock units assigned to the Upper Jurassic are the Tuwaiq Mountain limestone (Callovian), the Hanifa formation (Oxfordian?), the Jubaila limestone (Kimeridgian), the Arab formation (late Upper Jurassic) and the Hith anhydrite (probably Upper Jurassic). The two lowermost units, the Tuwaiq Mountain limestone and the Hanifa formation, are important topographically in central Arabia but are known so far only in that portion of Arabia. Neither have been recognized in coastal wells and available paleontological evidence suggests that the two units must be either highly condensed or entirely lacking. Along its belt of outcrop in central Arabia the Jubaila limestone is dominantly of shallow-water facies. Fine-grained limestone with layers of cleanly washed calcarenite prevail. In coastal Hasa the basal part is mainly dark, usually black, argillaceous limestone with varying amounts of black calcareous shales. The upper five-sixths of

the Jubaila is primarily fine-grained limestones interbedded with varying amounts of fine-grained calcarenite. Clean calcarenite, often coquinal, is limited to thin layers in the uppermost part. The Jubaila is productive in Abu Hadriya and in the Abqaiq area.

Rocks of the Arab formation show increased paleogeographic differentiation over those of the Jubaila, particularly in the coastal area, although the general pattern of lateral change seems to be simple. Little is known of the true rock sequence of the outcrop as extensive solution-collapse phenomena have nearly eliminated outcrops of the anhydrite. For this reason a subsurface section has been used as a type section. The Arab is composed of rocks laid down between four main cycles of desiccation, each of which starts at the base with apparently normal marine limestone deposition. The carbonate portions of the four cycles have been designated informally 'A', 'B', 'C' and 'D' members in order from top to bottom. The 'D' member is the principal oil-productive zone with minor local accumulations in the other members. Optimum reservoir conditions are present in the 'D' member in the northeastern Ghawar and Abqaiq areas. The 'D' member in these areas is a calcarenite, primarily of the pellet type although there is considerable true oolite with well developed concentric structure. True oolite is nearly absent in central and southern Ghawar. In contrast, the 'D' member of Dammam, Qatif, Bahrain and Qatar shows extensive facies change from fine-grained limestone to calcarenite. To the south in Ghawar the proportion of anhydrite between the 'C' and 'D' members progressively increases at the expense of the carbonate rocks of the 'D' member. The overall thickness of the 'D' member plus that of the anhydrite between 'C' and 'D' members is nearly constant over this same area. Information now available on the 'D' member suggests that the area of thick development of clean, current-washed clacarenite was a bar or the margin of a shelf. Apparently to the west, rocks of lagoonal facies occur instead of the calcarenite whereas a deeper water facies, composed mainly of lime mud deposits, seems to have been present to the east. The upper thinner limestone units, the 'A', 'B' and 'C' members, show far less extensive oil accumulation than the 'D' member. They also show more rapid increase of anhydrite to the south and west at the expense of the limestone.

No fossils have been found in the Hith anhydrite but it is presumed to be Upper Jurassic since it seems to close the depositional cycle which started with the Arab formation of apparent late Jurassic age.

Cretaceous

Saudi Arabian rock units assigned to the Lower Cretaceous are the Sulaiy limestone (Neocomian?), the Yamama formation (probably Neocomian), the Buwaib formation (probably Aptian) and the Biyadh sandstone (Aptian-Albian). The Sulaiy is a compact, fine-grained limestone with occasional layers of calcarenite and minor amounts of anhydrite at the base. The Yamama is a calcarenite alternating with fine-grained limestone. Exact equivalents of the Buwaib formation and Biyadh sandstone of the outcrop have not been worked out for the coastal section. Above the Yamama in the coastal section, however, are 1600 feet of Lower Cretaceous, a lower 700 feet of limestone overlain by 650 feet of sandstone and shale and an upper 250 feet of dolomite and limestone. The sandstone-shale unit is the equivalent of the Zubair producing zone of southern Iraq and is productive in Safaniya field. The Sulaiy and the Yamama have not produced oil to date in Saudi Arabia but there have been shows in the Yamama (the approximate equivalent of the Ratawi Zone which is productive in the Saudi Arabia-Kuwait Neutral Zone).

Upper Cretaceous rocks are represented by the Wasia formation (Cenomanian) and the Aruma formation (Maestrichtian and Campanian?). The Wasia in outcrop is only some 140 feet thick as compared with a section of 1200 to 1800 feet in coastal wells. The outcrop section is predominantly cross-bedded sandstone and red and green, silty shales. The coastal section is composed of a lower 700 to 1300 feet of sandstone and shale with minor beds of lignitic shale in the lower part and an upper section averaging 500 feet in thickness composed of limestone and red and green shales. These sands (Bahrain Zone) are productive in Safaniya field where they are divided into two units, a lower sand at the base followed by 150 feet of shale and limestone and then an upper sand.

The Aruma formation is approximately 500 feet thick at the outcrop type section and of comparable thickness in the coastal area. Lithology is essentially limestone with lesser amounts of shale at the base and at the top.

Post-Cretaceous

Paleogene rocks include the Umm er Radhuma formation (Paleocene-Lower Eocene), the Rus formation (Lower Eocene) and the Dammam formation (Lower and Middle Eocene). All are predominantly limestone and dolomite with minor amounts of marl and shale and, in the Rus formation, considerable anhydrite.

The Neogene consists of the Hadrukh formation (Lower Miocene?), the Dam formation (Miocene) and the Hofuf formation (Miocene or Pliocene). The lithology is largely sandstones, shales, sandy cherty limestones and marls.

STRUCTURE

General

Figure IV shows the approximate outlines of the main structural provinces of the Arabian Peninsula. The western portion is covered, for the most part, by a pre-Cambrian basement complex of igneous and metamorphic rocks partially overlain by volcanics in the west central portion and with major masses of extrusive volcanics in the Asir-Yemen Highland. To the north and north-west of the pre-Cambrian outcrops is a considerable area of Paleozoic rocks which dip gently east to nearly north. The entire western portion of the peninsula is a region substantially faulted by tensional and/or torsional shearing.

Bordering the 'shield' on the east is a long arcuate belt called the Interior Homocline of Paleozoic, Mesozoic and Eocene sediments which, in the northern segment, dip north-north-east at an average rate of not more than 4 meters per 100 kilometers. Dips, in the southern segment of the homocline, are of about the same magnitude toward the east-southeast into the Rub' al Khali, a vast basinal area in which some exploratory work has been done, but which is still poorly known. Infrequent shear lines with small displacement are found in both segments. Solution-collapse structures, minor local undulations and linear structural features of very low relief are typical in the north. The homoclinal area is perhaps 1200 kilometers long and 200 to 300 kilometers wide. Its eastern lower slopes are marginal or doubtful areas masked by Neogene sediments. From the sparse data at hand, these slopes seem fundamentally a continuation of the Interior Homocline

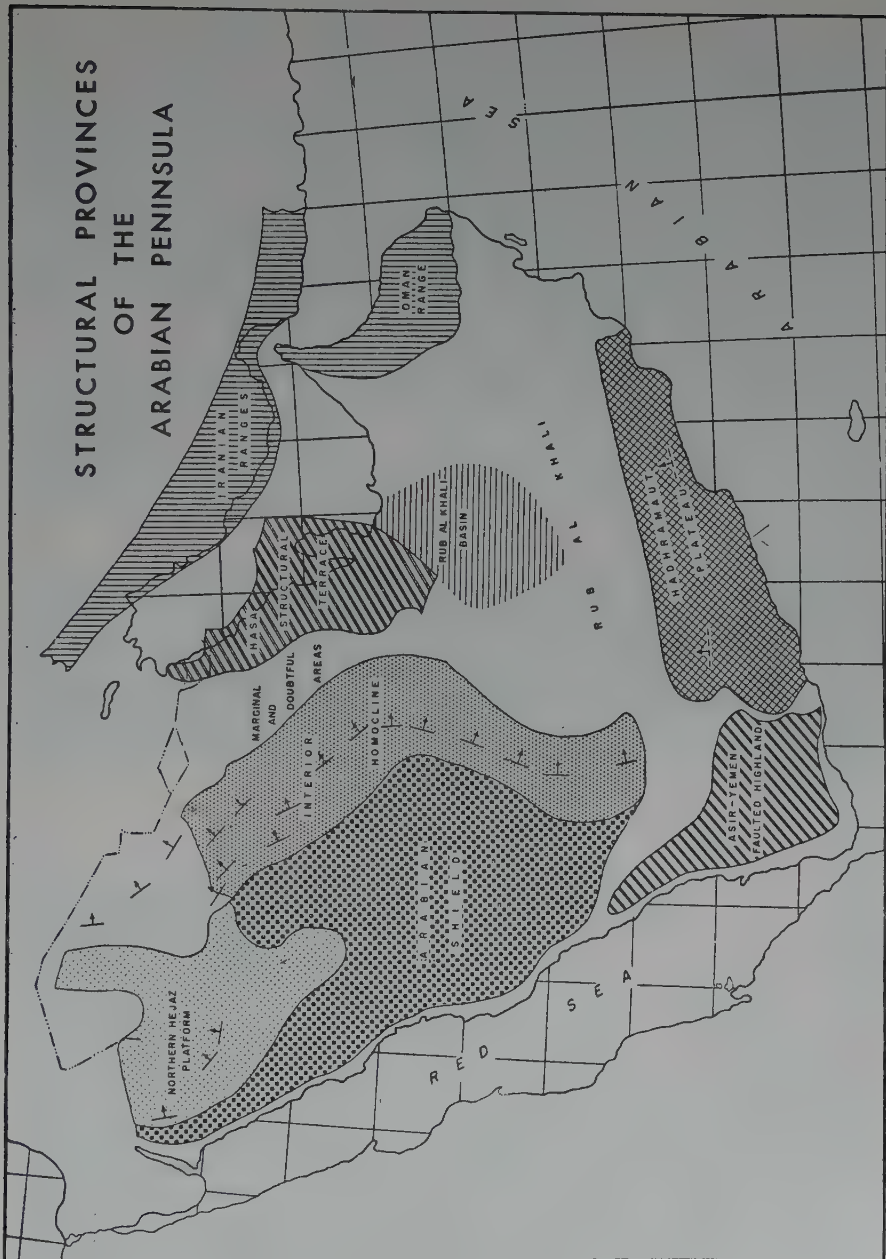
STRUCTURAL PROVINCES
OF THE
ARABIAN PENINSULA
IRANIAN RANGES
OMAN RANGE
HASA STRUCTURAL TERRACE
RUB AL KHALI BASIN
RUB AL KHALI
HADHRAMAUT PLATEAU
MARGINAL AND DOUBTFUL AREAS
INTERIOR HOMOCLINE
ARABIAN SHIELD
ASIR-YEMEN FAULTED HIGHLAND
NORTHERN HEJAZ PLATFORM
RED SEA
ARABIAN SEA

FIGURE IV

that may have been subjected to some structural disturbances and/or interruptions of sedimentation.

Immediately to the east of these marginal areas is the Hasa Structural Terrace, a slightly warped, relatively flat structural plane with minor undulations of low relief and irregular form. Structural elevations decrease progressively but very gradually to the northeast, east and southeast. On this plane is superimposed a pattern of generally north-south trending, major anticlinal axes. All known productive areas of Saudi Arabia as well as those of nearby Kuwait, Bahrain Island, Qatar and Kuwait Neutral Zone are within this structural province.

Although the Oman and Iranian Ranges were subjected to strong, compressional deformation during the late Tertiary, no evidence of simultaneous tectonic activity of this order has been recorded in central and northeast Saudi Arabia. A limited amount of tensional faulting in central Arabia may possibly have taken place as late as this.

Tilting, at various times, has resulted in unconformities at which truncation has eliminated older rocks on a regional scale at as low a rate as a fraction of a meter per kilometer. Some unconformities of this type are pre-Permian, pre-Lower Jurassic, pre-Upper Jurassic, pre-Middle Lower Cretaceous and pre-Middle Cretaceous. Pre-Upper Cretaceous and pre-Miocene unconformities are manifested in truncation of beds on the crests of individual folds.

Producing Areas

The two most important major anticlinal axes located within the Saudi portion of Hasa Structural Terrace are En Nala and Abqaiq-Qatif. The productive structures of Abqaiq and Qatif (Fig. V) are elongated anticlines which may have originated by deep-seated shearing. Associated with Abqaiq is a rather poor positive gravity anomaly, whereas Qatif shows a well developed one. Abqaiq is some 70 kilometers long by 20 kilometers wide with a gently curved major axis trending about N. 15° E. It is an essentially symmetrical anticline with a low, broad northern extension and closure of about 1500 feet at the top of the Arab 'D' member. Qatif is slightly asymmetric, broad to the south, narrowing northward with its major axis trending N 20° W, and slightly concave westward. About 350 feet of closure

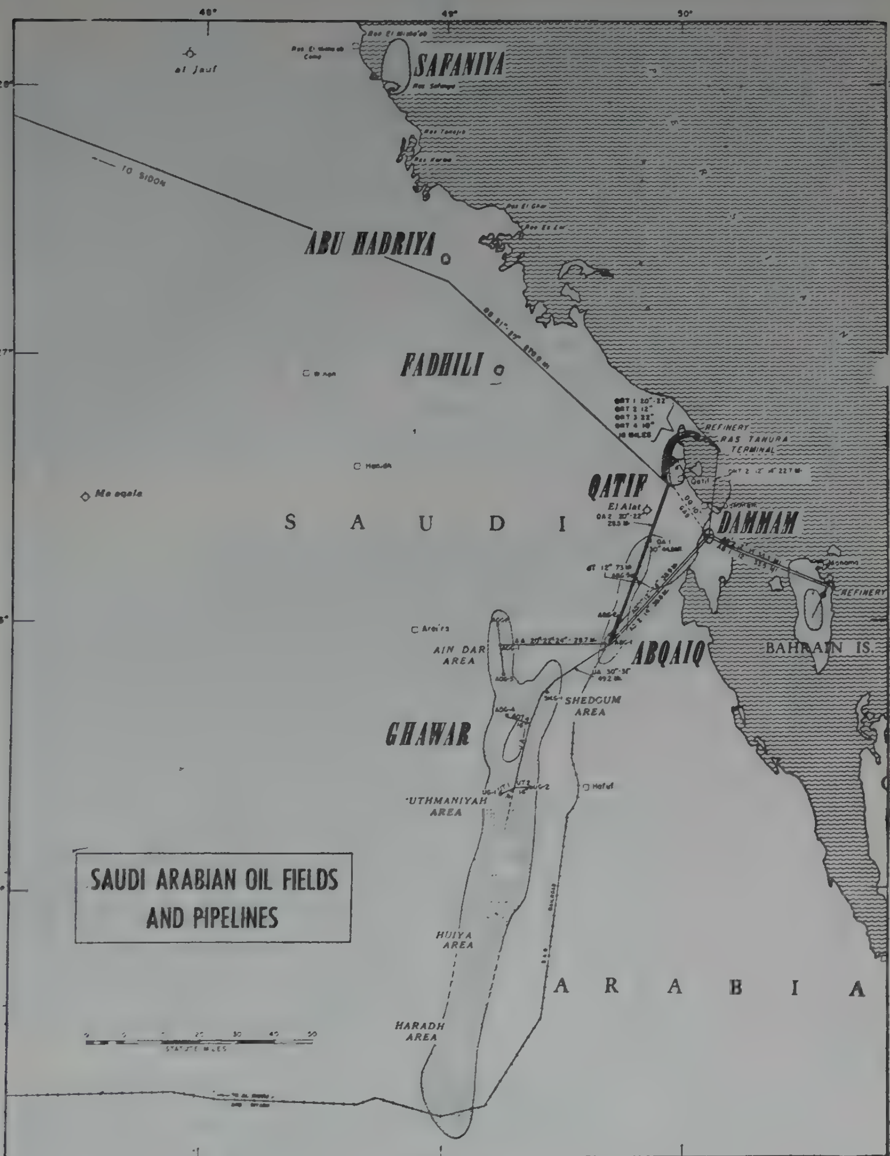
SAFANIYA
ABU HADRIYA
FADHILI
QATIF
DAMMAM
ABQAIQ
GHAWAR
REFINERY
RAS TANURA
TERMINAL
El Alat
AIN DAR
AREA
SHEDGUM
AREA
'UTHMANIYAH
AREA
HUIYA
AREA
HARADH
AREA
BAHRAIN IS.
TO SIDON
al Jauf
S A U D I
A R A B I A
SAUDI ARABIAN OIL FIELDS
AND PIPELINES
48°
49°
50°
28°
27°
26°
25°

FIGURE V

is proven at the Arab Zone with limiting closure to the west and south and the steeper flank on the east.

En Nala Axis extends from the southern tip of Haradh northward for a distance of 225 kilometers through the producible areas of Haradh and Huiya and the present productive areas of 'Uthmaniyah, Shedgum and 'Ain Dar'. These five 'areas' are known collectively as Ghawar field. Beyond the northernmost producer of 'Ain Dar', the axis extends probably at least 150 more kilometers to include Fadhili field. The axis is made up of an essentially continuous series of linear anticlines with gentle north plunges. Subtle surface expression is seen in the south where elevations are greatest. Marked reflection of the axis on gravity maps plus the general linearity of the individual structures suggest origin as a result of shear along major basement weaknesses. Perhaps coupled torsional effects may account for the variation in orientation of the different axes. Flank dips approach 10° to 12° at the producing zone with structural relief as great as 1200 feet.

Haradh [Structure Contour Map Ghawar, (Figure VI)] is a large, asymmetrical anticline, with a straight east flank and a long northern 'nosing' into the Huiya area with apparently no 'saddle' between the two. Huiya is a north-plunging, narrow anticlinal fold with its plunge interrupted by minor closures. 'Uthmaniyah is an elongate anticline, apparently composed of two brachyanticlines, the western one considerably lower structurally. The western axis trends generally north-south and the eastern one north-south to approximately N 15° E where it joins Shedgum. Shedgum is also an elongate anticline with its major axis trending N 15° E. 'Ain Dar is an elongate anticline with two structural highs separated by a 'saddle'. The axis of the northern high trends in a north-south direction, while that to the south is oriented approximately N 15° E. Shallow structure at Fadhili, as determined by structure drilling, indicates a somewhat irregular brachyanticline elongated in a northwest-southeast direction, but this is subject to further check.

Dammam Dome is not associated with any major anticlinal axis. It is a faulted dome with the longer axis trending about N 10° W and with a central graben, the bounding faults trending about N 60° W with throws up to 400 feet dying out peripherally. Major faulting does not extend above the Wasia-Aruma unconformity. The type of struc-

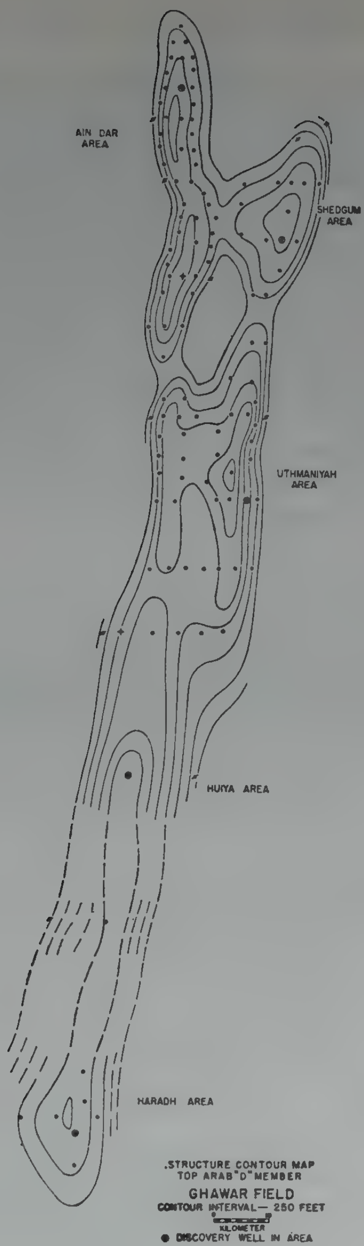
AIN DAR
AREA
SHEDGUM
AREA
UTHMANIYAH
AREA
HUIYA AREA
HARADH AREA
STRUCTURE CONTOUR MAP
TOP ARAB "D" MEMBER
GHAWAR FIELD
CONTOUR INTERVAL— 250 FEET
KILOMETER
DISCOVERY WELL IN AREA

FIGURE VI

ture with the presence of a gravity minimum centered about 3 kilometers from the apex of the surface high has led to the supposition that Dammam Dome is a shallow expression of a deep-seated salt plug. At the top of the Arab Zone, closure is substantially over 700 feet.

Abu Hadriya is another dome elongated in the direction N 10° W. Its subsurface structure has not been delineated, and its origin is unknown. Two deep wells, the discovery somewhat down the north plunge and a second southeast of the discovery, indicate a relatively steep east flank. Closure may be as great as 1200 feet at the producible zone.

Safaniya is a structure considerably more elongate than Dammam and, on present evidence, somewhat more so than Abu Hadriya. It appears to be a relatively simple fold with an axial trend slightly east of north and with very gentle flank dips. Closure at the productive zone is of the magnitude of 550 feet.

EXPLORATION AND DEVELOPMENT

Structure drilling was introduced in the Qatif-El Alat area in the fall of 1936 and the seismograph at Abu Hadriya in the spring of 1937. With the advent of gravity work at Dammam Dome early in March, 1939, the list of major methods of exploration was almost complete. Many refinements have been made in the intervening years, but the basic pattern of exploration remains unchanged. The post-war years have seen the addition of the magnetometer to the gravity parties, and photogeology has been used to advantage on older rocks. Offshore structure drilling and seismic surveys have been carried out in the Persian Gulf. Slim holes for stratigraphic information have been drilled as deep as 5000 feet with light, portable rigs.

Dammam is a surface structure with abundant outcrops and was mapped with plane table before the first hole was drilled. Surface indications of structure at Abu Hadriya led to a seismic survey which resulted in the location of the discovery well, completed in March 1940. This preceded by eight months the opening of Abqaiq as a producing field. Definition of Abqaiq was by structure drill. Unsuccessful wildcats were drilled at Ma'aqala (1940) and at Al Jauf (1944) during the war years. In June 1945 Qatif was discovered. This, like Abqaiq, was an area in which surface indications suggested structure but which necessitated the structure drill to confirm and define. Pro-

duction, which had averaged a little less than, 15,000 barrels per day during the years 1940 through 1944, increased four-fold in 1945.

Following the war, exploration was intensified and is still continuing. As early as 1941 a few widely spaced structure holes had confirmed surface evidence of much of En Nala Anticline. Additional structure drilling in 1947 and 1948 revealed favorable closures along the trend, and wildcat locations were staked at 'Ain Dar and Haradh. Oil in commercial quantities were discovered at 'Ain Dar in June 1948 and at Haradh in February 1949. Fadhili, a structure drill prospect located more than 100 kilometers north of the discovery well at 'Ain Dar, was discovered the same month as Haradh. Gravimetric coverage of the 'Ain Dar area had been completed prior to staking the first location and, by the end of the 1950-51 field season, had been extended to the south to include Haradh. Semi-detailed structure drilling was carried on in the 'Uthmaniyah area during the fall of 1948 and in the Huiya area during the spring of 1951. The discovery well at 'Uthmaniyah was completed in April 1951.

Following 'Uthmaniyah the Shedgum area was opened in August 1952. This was another discovery by structure drill. Seismic methods had been found impracticable over all the central and southern portions of Ghawar, probably due to the presence of limestones at and near the surface. Seismograph is, however, credited jointly with structure drill in the discovery of Safaniya in August 1951. Safaniya Well 1 was ARAMCO'S first off-shore discovery. Huiya Well 1, on the En Nala trend south of 'Uthmaniyah, was found productive in December 1953, and with the completion, five months later, of Haradh Well 8, all doubts were removed as to the continuous productivity of En Nala from 'Ain Dar to Haradh, a distance of about 225 kilometers.

During the 1955-56 field season ARAMCO maintaned 3 seismic parties, 3 structure drill parties, 1 gravity-magnetic party and 1 surface mapping party in the field.

Although credit has been assigned here to different methods of exploration for the discovery of the various fields of Saudi Arabia, it must be emphasized that delineation of deep structure has been accomplished, for the most part, by deep drilling. Methods employed to evaluate Ghawar, for example, called for a minimum of wells sufficient to deplete the field at maximum efficient rates and, at the

same time, to obtain adequate reservoir information for production planning.

Initial 'stepouts' in Ain Dar were 5½ kilometers along the crest with profiles across the structure at intervals of every 11 kilometers. Offset wells on the profiles were spaced at intervals of from 1800 to 2750 meters. By the end of 1950, fourteen wells were completed in north 'Ain Dar (Fig. VI), an area 28 kilometers long and 8 kilometers wide was proved productive, and the structure was still open to the south. Drilling continued in Haradh and 7 wells had been completed in an area 24 kilometers long and 16 kilometers wide without having delimited the structure. When 'Uthmaniyah Well 1 proved productive, the first exploratory 'stepout' was 16 kilometers north followed by one 13 kilometers west of the 'stepout'. As drilling continued the Shedgum area appeared to be a part of the same structure. Following completion of the initial Shedgum well, distances between exploratory 'stepout' were greatly increased. Thirteen wells were used in outlining and developing the Shedgum area which is approximately 32 kilometers long and 11 kilometers wide. A well 26 kilometers south from 'Uthmaniyah resulted in proving Huiya productive, and a well the same distance north from Haradh furnished enough structural control and reservoir information to connect all five areas as a single reservoir.

Ten wells along the major and minor axes comprised the exploratory drilling at Abqaiq. Primary development was by two series of ring wells, one on the 6000-foot subsea contour and the other on the minus 6500-foot contour. In North Abqaiq, drilling followed a more or less block system of spacing with offset wells about 3 kilometers apart. Development at Dammam Dome followed a 200-250 acre pattern with no two wells closer than 450 meters. Exploratory wells at Qatif have been drilled along the major axis and along central and northern transverse profiles.

Secondary methods of recovery and pressure maintenance may necessitate more wells in presently developed fields. A secondary phase of development is now beginning at Abqaiq where 150 million cubic feet of gas per day are returned to the reservoir.

Table 2 shows the status of all deep wells drilled in Saudi Arabia by ARAMCO as of December 31, 1955.

TABLE 2
STATUS OF WELLS AT END 1955

Field	Producing	Shut in or Standing	Observation	Suspended	Abandoned	Drilling	Total
Abqaiq	50	14	4	0	1	1	70
Abu Hadriya	0	1	0	1	1	1	4
Dammam	25**	5	1	0	10***	0	41
El Alat	0	0	0	0	1	0	1
Al Jauf	0	0	0	0	1	0	1
Fadhili	0	1	0	0	0	0	1
Ghawar							
Ain Dar	44	5	2	0	1	0	52
Shedgum	11	0	1	0	1	0	13
'Uthmaniyah	18	17	3	1	1	2	42
Huiya	0	1	1	0	0	0	2
Haradh	0	7	1	1	0	0	9
Ma'aqala	0	0	0	0	1	0	1
Qatif	9	1	1	1	1	0	13
Safaniya	0	17	1	0	0	0	18
Stratigraphic Well	0	0	0	0	1	0	1
TOTAL	157	69	15	4	20	4	269

* Including two gas-injection wells.
** Including three gas wells.
*** Including two gas wells.

OIL

Origin

A hypothesis is favored which confines potential source beds of Arab 'D' member oil to the Jubaila and 'D' member itself. First evidence of the growth of the individual structures in which 'D' member oil is now found seems to have been in early Upper Cretaceous time, although it is probable that local structural disturbances occurred during the Lower Cretaceous. Calcarenite lenses of the 'D' member may have acted as stratigraphic traps to retain the oil in the general vicinity until the final concentration as a result of later folding. The same theory seems applicable to 'A', 'B' and 'C' member oils.

Occurrence

Below is a tabulation of Saudi Arabian commercial oil occurrences, characteristics of the oils and general reservoir data (Table 3).

TABLE 3

	Zones Being Produced	Gravity API	Minimum Depth	Estimated Productive Area
Abqaiq	Arab–D*	37°–38°	–5592 ft.	87,000 acres
Abu Hadriya	Hadriya producible	35°–36°	Unknown	Unknown
Dammam	Arab–A	35°–36°	–3940	12,000
	Arab–B	35°–36°	–4000	9,000
	Arab–C	35°–36°	–4170	7,000
	Arab–D	35°–36°	–4200	3,000
Fadhili	Fadhili producible	38°	Unknown	Unknown
Ghawar				
Ain Dar	Arab–D	34°–36°	–5700	135,000
Shedgum	Arab–D	35°–36°	–5642	65,000
'Uthmaniyah	Arab–D	33°–35°	–5360	260,000
Haradh	Arab–D producible	32°–33°	–5064	50,000
Huiya	Arab–D producible	33°–34°	–5098	Unknown
Qatif	Arab–C	31°–32°	–6850	21,000
	Arab–D	37°–39°	–7030	16,000
Safaniya	Bahrain producible	27°	–4931	64,000
	Zubair producible	31°	–6552	3,000

* Two wells at Abqaiq produce from the Jubaila and two from the Arab-C.

Handling and Processing

The oil passes through one of fifteen gas-oil separator plants to remove solution gas and, when it is to be shipped offshore, to one of three stabilizers for removal of hydrogen sulfide gas. It then may go to the Ras Tanura refinery (ARAMCO), the Bahrain Island refinery (Bahrain Petroleum Company, Ltd.), or, if to be shipped as crude and refined by the purchasers, direct to tanker at the Ras Tanura marine terminal or to Sidon on the Mediterranean through the 1723 kilometer 30-31 inch Trans-Arabian Pipeline. A total of 1458 kilometers of gathering and trunk lines (10″-31″) serve the fields. Nominal capacity of Ras Tanura refinery is 189,000 barrels per day.

At present only Abqaiq, Damman, 'Ain Dar, Shedgum, 'Uthmaniyah and Qatif have surface producing facilities. A pipeline is being built from Safaniya direct to Ras Tanura.

Production

Tables 4 and 5 show daily average production by fields for 1955, cumulative production by fields through 1955 and annual production for the years 1936 to 1955 inclusive.

TABLE 4

Field	Total 1955 Production	1955 Daily Average Production	Cumulative Production Through 1955
Abqaiq	95,772,837	262,391	1,124,339,877
Abu Hadriya	0	0	9,579
Dammam	18,189,127	49,833	336,577,679
Ghawar			
Ain Dar Area	126,046,082	345,332	565,052,628
Shedgum Area	47,955,903	131,386	75,604,063
'Uthmaniyah Area	53,703,145	147,132	134,359,917
Qatif	10,572,818	28,967	70,865,245
Total	352,239,912	965,041	2,306,808,988

TABLE 5

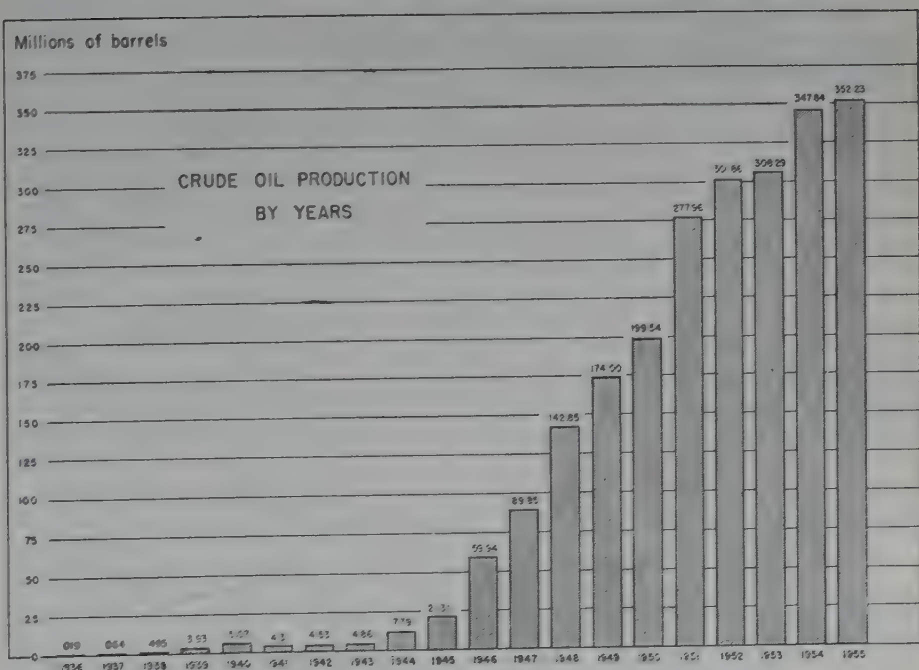

TABLE 5

Reserves

Reserves of Saudi Arabian fields are estimated to be between 30 and 35 billions of barrels.

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IRAN

(IRÁN)

OIL AND GAS IN SOUTHWEST IRAN

By The British Petroleum Co. Ltd. *

ABSTRACT

The oilfields of the petroliferous province of southwest Iran were discovered and developed between 1901 and 1951 by the Anglo-Persian, later the Anglo-Iranian Oil Company (now The British Petroleum Company Limited). After the nationalisation of the Iranian oil industry they were taken over by the international 'Consortium' in 1954 and have since been operated by the Iraanse Aardolie Exploratie en Productie Mij. (Iranian Oil Exploration and Producing Co.) The short paper which follows is a digest of the petroleum geology of the province as known in 1951 from 50 years work almost entirely by BP geologists.

The rocks of the southwest Iranian oil province were originally deposited in a great elongated basin, which was subsiding continuously from Permian times to late Cretaceous, and intermittently until late Miocene times. A late Cretaceous orogeny affected the northeastern part of the basin, and later, in Mio-Pliocene times, the Zagros Mountains were formed out of the basin by the Alpine orogeny. These folding movements produced the wide belt of large simple parallel anticlines trending northwest to southeast which now form the Iranian mountain and foothill belts. The high Zagros are composed of tightly folded Palaeozoic and Mesozoic rocks. Along the southwest of the mountains Tertiary limestones predominate. Southwest of the 'Mountain Front' (= southwestern limit of Lower Miocene (Asmari) limestone exposures) in the more gently folded foothill belt, these limestones are covered by the Lower Fars evaporites, whose behaviour as mobile strata overlying the main oil reservoir (Asmari Limestone) has produced enormous thickness variations and disharmony of folding, making surface geology an unreliable guide to underlying structure.

Within the foothill belt, where the Asmari Limestone reservoir is sealed by the overlying Lower Fars, seven major oilfields and one major gas field have

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A Portfolio of geological maps, sections, and stratigraphic columns of southwest Iran has been prepared by The British Petroleum Company Limited and is being presented to this Congress. Copies of this Portfolio will later be on sale to members of the Congress. Readers are referred to the contents of this Portfolio for greater stratigraphical and structural detail than can be given in the present short note.

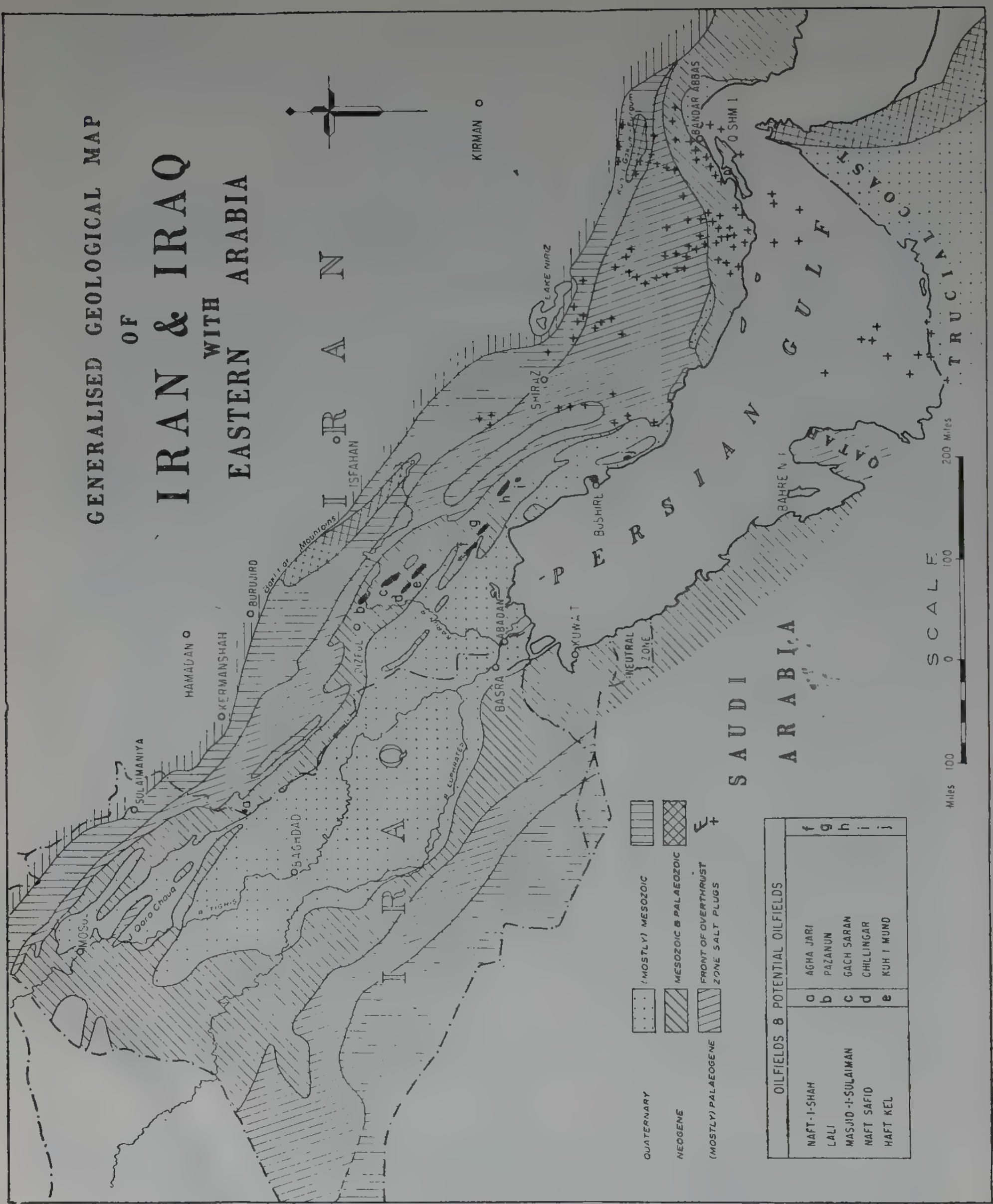

Figure 1. Geological Map showing position of oilfields.

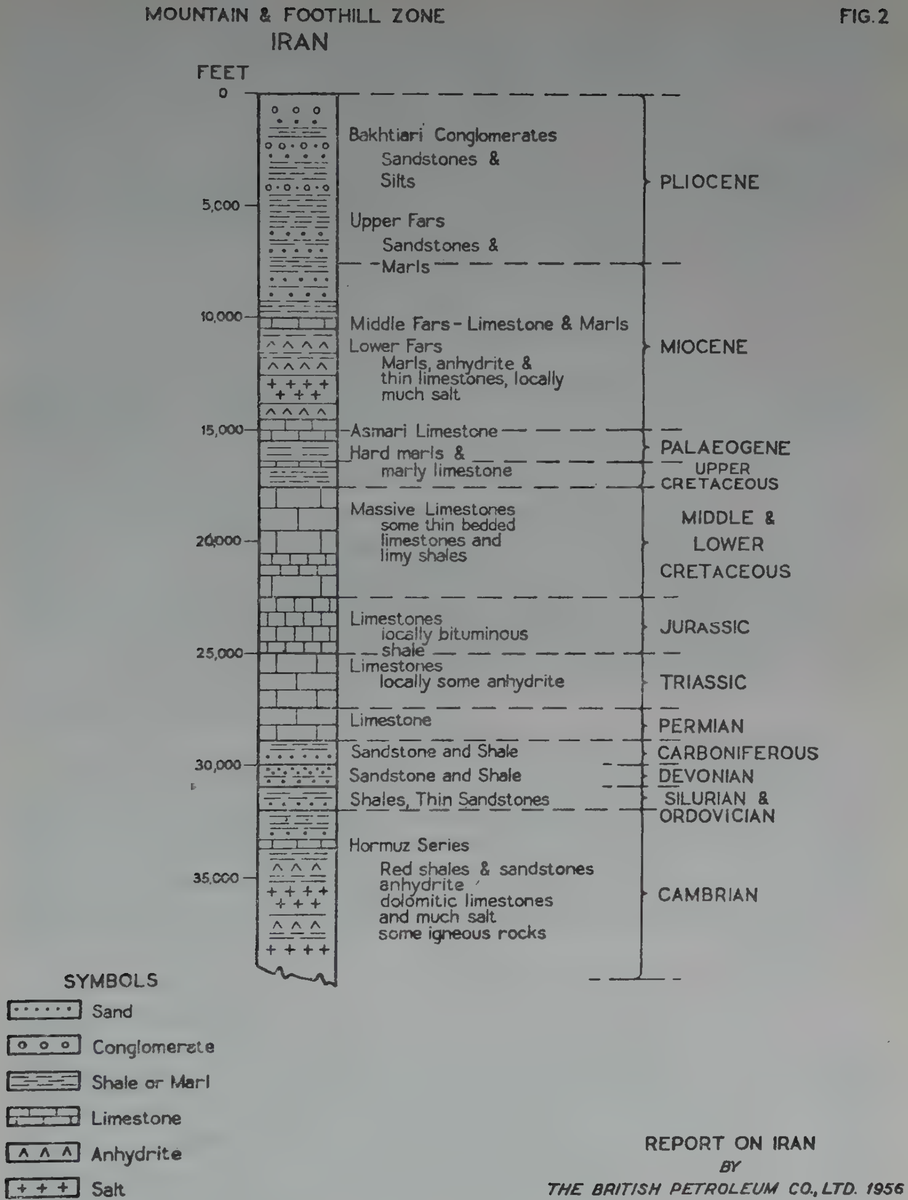

Fig. 2. Generalised Stratigraphic column.

so far been discovered. One of these field extends across the boundary into Iraq. All these fields have been on production. In addition, one large field of heavy oil, and one small oilfield have been discovered but not produced.

GEOGRAPHICAL DISTRIBUTION OF OIL AND GAS PRODUCING PROVINCES

The whole of southwest Iran forms one petroliferous province, the oilfields of which lie in the foothills of the Zagros Range. The province continues both structurally and stratigraphically northwestwards into southeast Iraq. (See Fig. 1 Map.)

GEOLOGICAL DESCRIPTION

The oilfields of southwest Iran lie in the foothills of the Zagros Mountains, whose great folds stretch from the north of Iraq to the mouth of the Persian Gulf. The sediments involved in the Alpine orogeny in this region were originally laid down in a great depositional basin, whose axis approximated to the present Tigris/Euphrates valley and its continuation in the Persian Gulf, but whose deepest part shifted throughout the ages (Falcon, 1956). Subsidence continued from Permian to Cretaceous times, the sediments laid down throughout this long period of time being dominantly calcareous. To the southwest the basin was bounded by the stable foreland of Arabia.

Stratigraphy and Geological History

The generalised stratigraphy of the Iranian oil province is summarised in Fig. 2. The sedimentary succession (Cambrian to Pliocene) has been described by G. M. Lees (1953), and (Triassic to Lower Miocene) in greater detail both stratigraphical and palaeontological by Kent, Slinger and Thomas (1951). The following is a brief outline (Lees, 1948).

During the Palaeozoic, sedimentation was not continuous, but there is no evidence of any angular discordances indicating important movements. The Cambrian is noteworthy for its salt deposits which have subsequently intruded their cover to form the great salt plugs of the Persian Gulf area. Ordovician to Carboniferous periods are poorly represented as thin shales and sandstones, but from the Permian onwards to early Miocene sedimentation was continuous and in general terms remarkably constant, the deposits formed being mainly calcareous. Thick limestone formations alternated with marly limestones or limy

shales and, locally, reef limestones were found, flanked by more bathyal conditions. At intervals, particularly in Jurassic, Cretaceous and Eocene, foul bottom conditions resulted in the deposition of black sulphurous limy muds which on consolidation became the poly-bituminous marls and marly limestones thought to be of importance as source rocks of the oil. Otherwise normal marine conditions prevailed with occasional lagunar deposition, as shown by the anhydrites, interbedded with limestones and marls, in the Triassic and Jurassic.

The first great change in sedimentary conditions began in the Oligocene and Lower Miocene; gentle warpings and undulations caused shoal areas in some places and concentrated lagunar conditions in others. Extensive evaporite deposits —the Lower Fars formation— locally attained many thousands of feet in thickness of alternating anhydrites, salt and marls. This lagunar phase was ended before the end of the Middle Miocene by a return to normal marine conditions, but after a short time the sea withdrew and throughout the Upper Miocene and Pliocene a great thickness of marls and sandstones —the Upper Fars— was deposited, followed by the silts, sandstones, and conglomerates of the Bakhtiari series, which were accumulated in the great synclines then in slow process of development.

Surface Indications of Hydrocarbons

Hydrocarbon indications are common throughout the Zagros mountain belt and foothills. They are commonest in the Cretaceous to Miocene part of the succession. They include most known types, but of particular interest here, is the phenomenon produced by the escape of hydrocarbon gases, which is locally known as 'gach-i-turush' (= Persian for 'sour gypsum') (Thomas, 1952).

Source, Reservoir, and Cover Rocks

"The difficulty of assigning a source to the oil of the... Persian fields is one embarrassment of possibilities" (Lees, 1953). These various possibilities have been discussed in the literature by Lees, 1933, Lees and Richardson, 1940, Thomas, 1948, and Lees, 1953, the generally held view being that the main source lies within the Mesozoic-Palaeogene succession.

The well-known reservoir of the Asmari Limestone has been described in detail by Lees, 1933, and Thomas, 1948. A lower reservoir exists in the Middle Cretaceous Limestone, as proved in the Lali field.

The function of the Lower Fars evaporites as cover rocks to the oil reservoir in the Asmari Limestone, and the factors contributing to its sealing action, have been considered by O'Brien, 1948, and by S. Elder, 1956.

Structure

The first tectonic movements affecting the present oilfield belt took place (Lees and Richardson, 1940), in Turonian/Senonian/Maestrichtian times on the northeast margin of the basin. Complex oscillatory epeirogenic movements occurred during Oligocene/Lower Miocene times.

The main Alpine orogeny began in late Miocene times, when the sediments from Palaeozoic to Tertiary, laid down in the central portion of the basin, were folded into a series of northwest to southeast trending folds, and the Zagros mountains emerged. Detrital estuarine and fresh-water sediments derived from the rising anticlines, were deposited in the southwest in late Miocene and Pliocene times (Upper Fars and Bakhtiari).

After the deposition of the Upper Fars the main Tertiary folds developed rapidly (Falcon, 1956) and deposition was controlled by the structural features so formed, the fresh-water Pliocene deposits being thickest in the important synclinal areas. The subsequent history of the head of the Persian Gulf has been discussed by Lees and Falcon, 1952.

The present producing oilfields lie in a zone about 30 miles wide in the moderately folded foothills to the southwest of what BP geologists usually call "The Mountain Front", i.e. the southwest limit of the pre-Fars outcrops. The pre-Fars rocks have been folded into a simple structural pattern composed of a broad belt of long parallel northwest to southeast trending anticlines. Many of these are asymmetric with steeper dips on the southwest flank which in some cases tends to be vertical or even overturned. The overlying Lower Fars evaporite formation, however, is not folded concordantly with the pre-Fars. It is much faulted and often overthrust towards the southwest as a result of the

incompetence of the formation and the plastic nature of the salt and gypsum within it.

To the northeast lie the high Zagros mountains, whose stratigraphy and palaeontology have been described by Kent, Slinger and Thomas, 1951. These are in turn bounded on the northeast by a zone of strong overthrusting. To the southwest of the oilfield belt, the Miocene-Pliocene folds are covered by the alluvium of the Tigris-Euphrates valley and the waters of the Persian Gulf.

The regional structure of the Iranian ranges was originally described by de Böckh, Lees and Richardson (1929), but much of this has now been superseded by later knowledge. O'Brien (1948 and 1956) has described the tectonic behaviour of the Lower Fars and its resulting effects on the structure overlying the oilfields. The salt plugs of the south have been described fully by R. K. Richardson (1926, 1928), and by Harrison (1930, 1931). K. Washington Gray (1950) has described a tectonic 'window' in the complex tectonic belt on the northeastern margin of the area at present under discussion.

GEOGRAPHICAL AND GEOLOGICAL DISTRIBUTION OF THE OIL AND GAS FIELDS WITHIN THE PROVINCE

The geographical distribution of the southwest Iranian oilfields is shown on the attached map (Fig. 1). Geologically they occur in two structural embayments, the Sirwan (Diyala) to the northwest, which includes Naft-i-Shah, and the Diz-Karkheh to the southeast, which contains the main Khuzistan group of fields.

The Iranian fields are (from north to south):

a. Naft-i-Shah		Northern Area
b. Lali c. Masjid-i-Sulaiman d. Naft Safid e. Haft Kel		Central Area
f. Agha Jari g. Pazanun (gas, not at present produced) h. Gach Saran		Southern Area
i. Chillingar j. Kuh-i-Mund	not produced	Gulf Area

The important fields will be described in that order in the following two sections.

Oilfield	Date of Discovery	Prod. began	Producing area in sq. miles as at 1.1.1950	Depth to top of prod. limestone in feet	A.P.I. Gravity of crude	% Sulphur in crude	Production in 1st half of 1951		Cumulative net production to August 1951 (millions of barrels)
							Daily rate in barrels	Average per well in barrels per day	
Producing fields									
Naft-i-Shah *	1923°	1935		2,400	43.0°	0.6			
Lali	1938	1948	10	5,000	35.6°	0.69-0.95	13,000	3,250	13
Masjid-i-Sulaiman	1908	1911	54	600	38.0°	1.13	54,000	2,160	862
Naft Safid	1934	1945	30	3,000	35.4°	1.5	21,000	3,500	35
Haft Kel	1928	1928	45	2,000	37.8°	1.22	170,000	9,000	1,000
Agha Jari	1937	1945	40	4,500	34.6°	1.42	350,000	17,500	428
Gach Saran	1928	1940	60	2,500	32.0°	1.6	42,000	10,500	131
TOTAL							650,000‡		2,469‡
Other fields									
Pazanun (gas) ⊗	1937	1943	—	5,500	—	—	—	—	—
Chillingar	1924	—	—	2,000	32.0°	—	—	—	—
Kuh-i-Mund	1931	—	—	900 (Eocene)	c. 5.0°	—	—	—	—

* Data applies to Naft-i-Shah sector only (excluding Naft Khaneh).
⊗ Only gas has, as yet, been found at Pazanun. Condensate was produced for a short time during the war.
‡ Excludes Naft-i-Shah.
° Date of discovery of oil in the Iraq sector of the structure.

STRATIGRAPHY AND STRUCTURE OF THE MORE IMPORTANT FIELDS
HISTORY AND METHOD OF DISCOVERY OF THE MAIN FIELDS
(These subjects are discussed together)

(a) NAFT-I-SHAH. (Fig. 3 —Cross Section).

Position: The Naft-i-Shah oilfield lies 270 miles northwest of Masjid-i-Sulaiman at the northwest end of the Pusht-i-Kuh mountain range. The structure crosses the Iranian/Iraqi boundary, the part of the field in Iraq being known as Naft Khaneh.

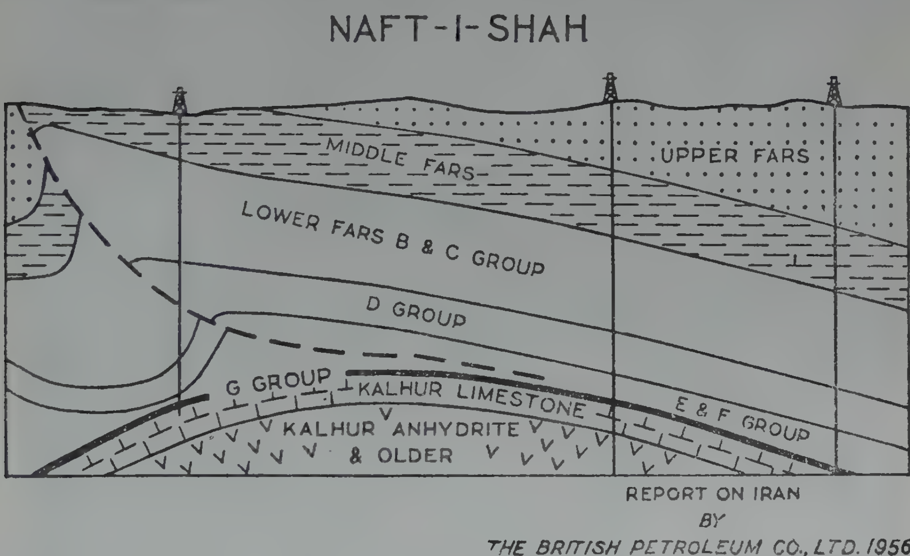

Figure 3. Cross-section Naft-i-Shah.

Surface geology: The surface expression of the underground structure is a long, sinuous, asymmetrical faulted anticline. It begins in Upper Fars beds in the Iranian foothills and runs in a general southeast to northwest direction for about 50 miles until its identity is lost in recent gravels northwest of the Sirwan River. The anticline is in Upper Fars, Lower and Upper Bakhtiari sediments along most of its length but at its culmination astride the boundary, Lower Fars beds are exposed. Its breadth is about 5 miles from one flanking syncline to the other.

The northeast flank is much gentler than the southwest, which in a long narrow belt has dips of 75-90°. These dips are associated with a thrust-fault which disrupts the anticline, running roughly parallel to, but just southwest of the axis. This thrust has resulted in the surface axis being displaced about half-a-mile to the southwest of the underground Asmari axis. The anticline pitches at between 3 and 5° in both directions from the crest maximum, with no significant reversals of pitch throughout its entire length.

Oil Indications: Copious active oil and gas seepages, which have produced much 'gach-i-turush' (sour gypsum —a product of the action of gasses on marl, gypsum and limestone) and the development of strong secondary aragonitic limestones, extend over a large area and drew early attention to the oil possibilities of the structure.

History: The large oil and gas seepages were first described (in an unpublished Company report) as far back as 1903, but the area was not mapped until 1918. Drilling began in 1919, but progress was slow because of mechanical and other troubles. The first well proved to be the discovery well, when in May 1923 oil was found unexpectedly (In the Iraq sector). Uncertainty as to the nature and position of the reservoir continued, however, as the discovery well had blown wild, caught fire, and only been brought under control with difficulty, and the next 3 wells had been abandoned because of high pressure shows in the Lower Fars.

It was not until the remapping of the area in detail in 1924 that the conclusion was reached that the main reservoir would be a thick limestone, known in adjoining areas as Kalhur, immediately underlying the Lower Fars. It was considered that this was the equivalent in age and lithology of the upper part of the Asmari Limestone of southwest Iran, which by then was known to be the main reservoir of Masjid-i-Sulaiman. This was proved in 1932 when the first well to reach the Kalhur was drilled in the Naft-i-Shah sector, and penetrated the oil column. Until then production had been from the Lower Fars limestones; it is now known that these accumulations have free connection with, and are in pressure equilibrium with the Kalhur reservoir.

Little systematic field work was done after 1925, and modifications of the geological picture were brought about by the results of development drilling and the sporadic field work of successive resident geologists.

Underground Structure: The underground Kalhur and older rocks form a simple asymmetrical anticline, unaffected by thrust faulting though a few normal faults are believed to occur. Dips on the northeast flank of the Kalhur structure are 16-17° and on the southwest reach a maximum of about 60°. The depth to the top of the Kalhur is 2,400 feet. Thickness variations in the Lower Fars are less than in any of the other Iranian fields; it is thickest to the southwest of the Kalhur structure and thinnest over its northeastern flank. In this reduced disharmony between the Lower Fars and the producing limestone, the Naft-i-Shah field resembles more closely the Kirkuk field in Iraq than the more southerly Iranian fields. The structure, in comparison with the latter, is small and has less closure.

Reservoir: The Kalhur limestone has a maximum thickness of 215 feet and is underlain by 500 feet of anhydrite with only minor thin marl, limestone, and salt intercalations. No wells in the Naft-i-Shah sector of the field have drilled below the Kalhur. The reservoir limestone has an average porosity of about 16% and is thoroughly fractured.

Production: Commercial production began at Naft-i-Shah in 1935. The crude produced is of good quality, with a lower gravity (43° A.P.I.) and a lower sulphur content (0.6% weight) than any other southwest Iranian field. By August 1951, 6 wells had been drilled in the Iranian sector, of which 2 were on production in July 1951, when the operation of the Naft-i-Shah portion was taken over by the National Iranian Oil Co. The crude oil produced supplies the local north Iranian market and is treated at the Kermanshah refinery, 100 miles distant to the northeast. The Naft Khaneh sector, in Iraq, is operated by the Khanaqin Oil Co. (wholly-owned subsidiary of BP), whose production is piped to the Alwand refinery.

(b) LALI. (Fig. 4 —Cross Section).

Position: The Lali field lies 25 miles northnorthwest of Masjid-i-Sulaiman, astride the Karun River, whose deep impressive gorge divides the oilfield into two parts, the Lali Plain on the northeast or right bank and Lali Ambal on the southwest left bank.

Surface geology: The field underlies two synclines in Upper Fars/Bakhtiari rocks, which are sandwiched between the Lower Fars anti-

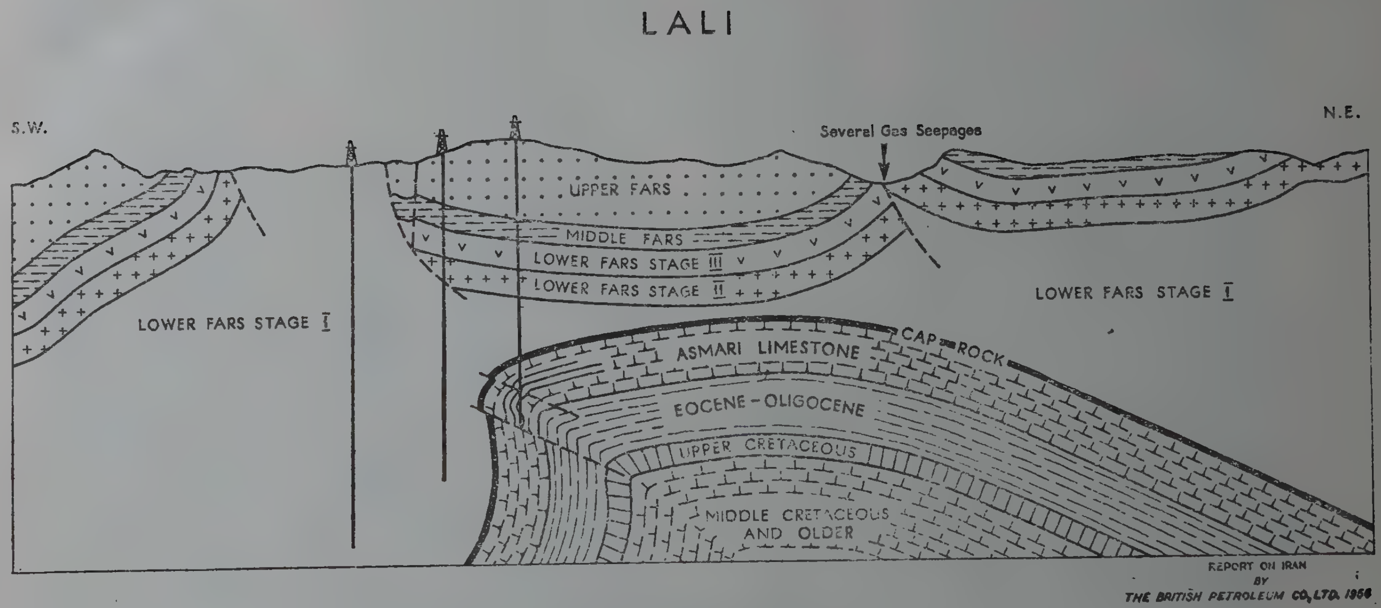

Figure 4. Cross-section Lali.

clines of the Lali Plain on the northeast and the Zeloi and Gach Moh Lower Fars structures on the southwest. Lower Fars salt crops out at the surface at Ambal in the only known exposure of salt of this age in the entire foothills belt, forming a salt dome 1 mile in diameter.

Oil Indications: There are two relatively small areas of gas seepages both of which occur close to faults in the Lower/Middle Fars.

History: Lali is the youngest of the Iranian oilfields and consequently its reservoir is one of the least thoroughly explored. The oil prospects were viewed favourably as early as 1918 in the belief that the reservoir rock was in the Lower Fars. After it had been established that the Asmari limestone was in fact the reservoir, the prospects of finding an Asmari structure in the Lali area were still considered to be good. Drilling in search of this structure began in 1925 in the adjacent Zeloi area, where 3 unsuccessful wells were drilled, and in the Pirgah area, where 2 further wells failed to find the structure in spite of a seismic reflection survey carried out in 1934 before the location of Pirgah No. 2. In 1935-36 a seismic refraction survey indicated that an Asmari axis lay to the northeast of the latter well, and Zeloi No. 4 was started in May 1936. It eventually reached the Asmari limestone at great depth, where it was found to be water-bearing. In 1936-37 a seismic refraction survey was done in Lali and contiguous areas. This work indicated the presence of an Asmari anticline directly below two of the major synclines in the area and about 3 miles southwest of the position indicated by a geological survey carried out in the same year.

Wells Lali 1 and 2, located on the geophysical evidence, began drilling in late 1937 and early 1938, and later in the year both wells found the Asmari and Lali was at last proved an oilfield. In an amusing account of the exploration and development of this field H. W. Lane (1948), wrote:

"This should be the end of the story, and by all rules of the game the development should have been plain sailing. The first well struck gas, the second drilled right through the limestone without getting more than a trickle of oil. The third well proved to be sited on the gas dome and was suspended. The fourth struck water, while the fifth missed the limestone altogether... the sixth well, sited in what was considered to be an area certain to obtain production, also missed the limestone... and it was decided to try directional drilling.

"This complicated operation was designed to deflect and steer the hole in a northeasterly direction where it was hoped to strike the flank of the structure

at a reasonable depth. The well was plugged and re-drilled from a point 4,000 feet from surface, the new hole being deflected at an angle of 15° from the vertical. Eight months of patient work followed, calling for over 1,000 different operations, some sections of the hole being drilled and redrilled several times before the correct deviation and direction was achieved. As the hole grew deeper with still no signs of the limestone it was evident that though a horizontal difference of 600 feet from the old hole had been obtained, this well too had missed its objective...

"But perseverance was to bring its reward. Returning to the first well the hole was deepened through the gas dome, a difficult and hazardous operation. Success came at last when in June 1946, at a depth of 5,800 feet, a production of 4,300 barrels per day was obtained... A second deepening job on No. 3 put Lali well and truly on the map with a production of about 28,000 barrels per day, and moreover explained why the much-sought structure had proved so elusive. It appeared that the limestone, usually so well behaved and normal in form, had, in this field, curled right over like the crest of a breaking wave..."

Development of the field thereafter proceeded gradually after the wartime suspension of activities. Before the building of a bridge across the Karun River (completed August 1950) one obstacle in the original development of the field had been the difficulty of transporting heavy material across the river, and by August 1951 only 4 wells had been drilled on its right bank, as compared with 11 on the left bank. At that time there were four wells producing from the Asmari and one, No. 2, which had been deepened in 1949-50 to the Cretaceous, producing from the lower reservoir; in addition there were two wells drilling.

Structure: The underground structure lies on the same general anticlinal line as Masjid-i-Sulaiman but is offset slightly to the northeast. Its size is about 15 miles long by 4 miles wide, but the field has not been completely explored. The top of the anticline is broad with a flattish zone just northeast of the axis. The southwest flank is very steep and, for some distance opposite the crest maximum, overturned. Drilling results have shown a large (11,000+ feet) Lower Fars Stage 1 salt accumulation on the southwest flank, and a similar one is thought to exist on the northeast flank, where dips are about 20°. The structure and the tectonic history of the area are complex, and one interpretation of them has been put forward by O'Brien (1948). The Asmari anticline rises gently for several miles from the saddle separating it from the Masjid-i-Sulaiman structure, before plunging more steeply to the northwest. The depth to the top of the Asmari is 5,000 feet, of which only 300 feet in the crestal area is made up of Lower

Fars Stage 1, notwithstanding the enormous thickness only a few miles to the southwest at Zeloi.

Reservoir: The thickness of the Asmari reservoir at Lali is over 1,000 feet (the discovery well found 1,200 feet), but, in spite of the strong folding, fissuring is less than in any other producing field in Iran. Also less good, is the estimated average matrix porosity, which is only 4.6%. Production from individual wells has therefore had to be restricted to prevent the drawing down of the gas/oil level. The length of the oil column in the Asmari is similar to that at Masjid-i-Sulaiman, but as a result of poorer fissuring and porosity conditions, productivity is expected to be less.

A second reservoir has been found at Lali in the Middle Cretaceous limestone. One well, after drilling 1,000 feet into the Cretaceous limestone, produced a large quantity of oil on test, and continued down to oil/water level, which was some 1,600 feet below that in the Asmari. The Cretaceous limestone therefore forms a separate reservoir, sealed by the intervening Upper Cretaceous/Eocene marls and marly limestones. Fissuring appears to be more frequent than in the Asmari but porosity remains low (estimated average matrix porosity 4%). The crude oil from the Cretaceous reservoir is similar to that of the Asmari (gravity 35.6° A.P.I.) but very slightly heavier, and with a slightly higher sulphur content (1.19% as against 0.69-0.95%).

Production: The first Asmari producer (L.2) came in June 1938 but later went to gas; this was the well which in 1949 was deepened to the Cretaceous. From the lower reservoir it produced initially 7,400 barrels per day but this was later restricted to 4,300 barrels per day because of the rapid decline in flowing pressure. At the time of the shutdown in August 1951 ten wells had been completed, of which 4 were Asmari producers, with a daily rate of 13,000 barrels per day.

(c) MASJID-I-SULAIMAN. (Fig. 5 —Cross Section.)

Position: The Masjid-i-Sulaiman field (originally known as Maidan-i-Naftun) lies about 50 miles northeast of Ahwaz and 20 miles east of Shushtar. It is the oldest of the Iranian fields and its geology and history are well known, so that only a brief outline is given here.

Surface Geology: The surface structure is that of a broad Lower Fars anticlinorium, intensely disturbed, with steep surface folds and

shallow thrust sheets resulting from the plastic nature of the gypsum. It runs in a northwest-southeast direction and is flanked to the northeast by a syncline exposing Upper Fars and Bakhtiari beds, and to the southwest by a Lower Fars thrust sheet.

Oil Indications: There are copious oil seepages and gas escapes in the crestal area. The presence of these led to the early drilling of the area.

History: Seven years after the granting of the Iranian concession to W. K. D'Arcy, the first producing well was brought in at Masjid-i-Sulaiman (then known as Maidan-i-Naftun) in 1908. This was the

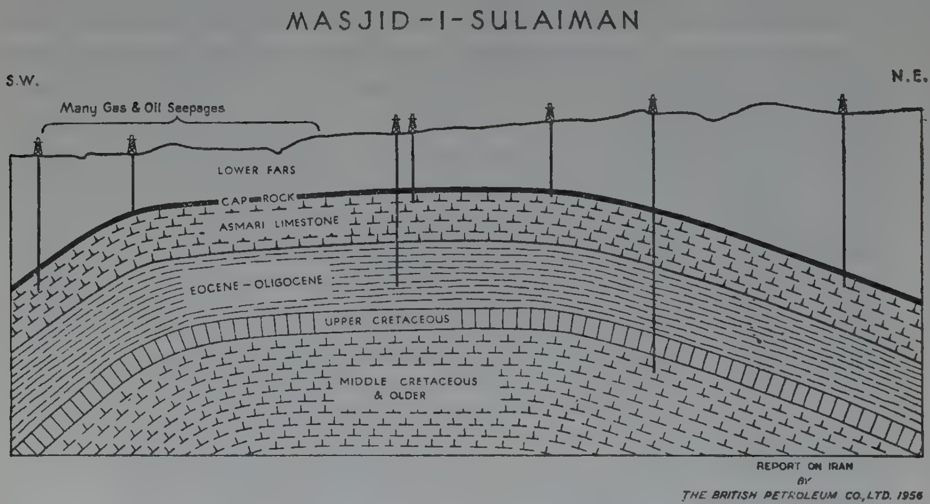

Figure 5. Cross-section Masjid-i-Sulaiman.

third area to be explored, after unsuccessful drilling at Chia Surkh in Iraq, and at Mamatain, southeast of the present Haft Kel oilfield.

The basis for locating wells in all these places was the presence of oil seepages and gas escapes combined with anticlinal structure. But at that time it was thought that the reservoir would be a sandstone within the Fars Series, and locations were made on anticlines in these rocks, which are now known to be structurally independent of the oil reservoir.

After the discovery of oil in 1908, exploration of the field continued by a gradual stepping out of the wells until the greater part of

the seepage area had been covered. It was found that the reservoir rock was a limestone but it was still thought to be in the Lower Fars. Owing to these misconceptions it was not until 1919, when the identity of the reservoir rock was proved by micropalaeontological means, that it became apparent that the surface structure did not coincide with the underground structure of the oil-bearing Asmari limestone. The early exploration of this (and the Lali) area, which revealed the magnitude of the problem of disharmony, has been described by Lees and Richardson (1940).

The development of the field was described in detail by Gibson (1948). It reached its maximum production in 1928, when the recycling of surplus products to the reservoir began.

Underground structure: The Asmari Limestone dome is flattish on top but asymmetrical, like most Iranian foothill structures, with steep dips on the southwest flank and gentler ones on the northeast. It pitches down to the southeast in direct line with Kuh-i-Asmari which is usually regarded as a visible replica of the Masjid-i-Sulaiman dome.

Reservoir: The Masjid-i-Sulaiman field is about 20 miles long by about 3¾ miles wide. The thickness of the Asmari Limestone is about 1,000 feet and the minimum depth to the top of the producing formation about 600 feet. The limestone at Masjid-i-Sulaiman is for the most part of low porosity, the mean for the whole being about 6%. The production history of the field and its mechanism —from fissures rather than from the pores of the limestone— has been published in detail (Gibson, 1948). The crude oil is of good quality, with a gravity of 38.0° A.P.I., and contains 1.13% sulphur by weight.

Three wells have been drilled into the Eocene marls and marly limestones which lie immediately below the Asmari Limestone. A small production of slightly different gravity oil was obtained from a thin limestone, whose oil/water level proved to be the same as that in the Asmari reservoir, i.e. it extends in a continuous plane through the core of the structure. Only one well has been drilled into the Cretaceous, the top of the Middle Cretaceous Limestone lying about 2,000 feet below the base of the Asmari. Cores from this well were oily but tests produced only water. It would seem that vertical migration has taken place from the Middle Cretaceous Limestone in spite of the 2,000 feet of intervening Upper Cretaceous and Eocene marls and marly limestones.

Production: The maximum production rate of the field was reached in 1928, when it was 118,000 barrels per day. Since then it has varied according to requirements but with a gradual decline. In August 1951 the daily rate of production was 54,000 barrels per day from 25 wells, and by that time the reservoir had a cumulative net production to its credit of 862 million barrels and a cumulative gross production of over a thousand million barrels. The field has produced from 115 wells but never from more than 31 wells at any one time.

(d) NAFT-SAFID (formerly White Oil Springs). (Fig. 6 —Cross Section.)

Position: Naft Safid lies 10 miles northwest of Haft Kel, of which structure it is a lower culmination.

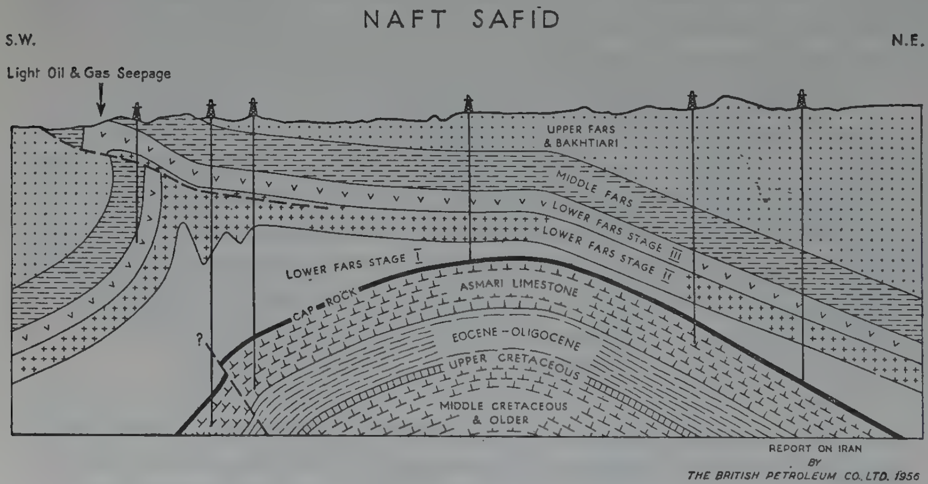

Figure 6. Cross-section Naft Safid.

Surface Geology: The surface structure is a long narrow asymmetrical anticline in Lower, Middle and Upper Fars rocks. It begins in Lower Fars to the southwest of Haft Kel and is strongly overthrust to the southwest in Stage 3 Lower Fars at its southeast end. It pitches down to the northwest for many miles with only minor reversals. Topographically it is dominated by the conspicuous red Upper Fars/Lower Bakhtiari scarp which runs along the northeast flank.

Oil Indications: The field is marked by a gas escape with 'gach-i-turush' in the crestal region near the thrust fault, with a seepage of light straw-coloured oil, which is regarded as a condensate from the escaping gas. This seepage was known from early days of A.P.O.C. exploration and gave its name to the field. There are other gas seepages one mile to the northwest and 3½ miles to the southeast.

History: A rapid reconnaissance of the Naft Safid area (then known as White Oil Springs) was made in 1909, but the white oil seepage had been known for some years. After a further examination in 1913, drilling was begun in 1914, but owing to lack of knowledge regarding the true reservoir rock, the two wells were abandoned in Lower Fars. The area was shut down between 1918 and 1934. A 1-inch survey was made in 1924, and a location to drill in search of the Asmari was recommended but not implemented because of the great depth (for the drilling outfits then available) to it.

In 1934 drilling began again and the third well struck gas in June 1935. The fourth well was also in the gas cap, and the fifth, in March 1938, was the first to strike the Asmari in the oil-column. Three more wells were drilled before the wartime shutdown of operations: one was a disappointing producer, the others penetrated gas/oil and oil/water level respectively.

Development began again after the war and the field came on commercial production in 1945.

Underground structure: The Asmari structure is a lower culmination on the same structure as Haft Kel, from which it is separated by a deep saddle to the southeast. To the northwest it pitches down continuously for many miles. The lenght of the field is 17 miles, and it is about 2 miles wide. The crest maximum lies some 1,500 feet lower than that of Haft Kel. Thickness of the Asmari is 900 feet, as at Haft Kel.

The axis of the Asmari anticline diverges from the surface axis from northwest to southeast, so that in the southeast it lies 1½ miles northeast of the surface fold. The structure is asymmetrical both in cross-section and longitudinally, the crest maximum lying much closer to the southeast pitching end than to the northwest. The Fars overfold is disrupted by thrust faulting with a maximum stratigraphic throw of 1,000-1,500 feet. The forward movement of the Fars cover rocks has

caused considerable attenuation of the saliferous Lower Fars, with a concomitant accumulation of that formation over the southwest flank.

Reservoir: The Asmari reservoir is long and narrow, and is in pressure equilibrium with Haft Kel, but with unusually high ratio of dome pressures to depth, resulting from the extremely long gas column. There are two gas domes, the southeast one being the main one. The Asmari limestone does not exhibit the very high productivity of Haft Kel and Agha Jari, although its porosity characteristics are as good. This lower productivity must be attributed to a scarcity of fissures.

No well has yet been drilled in Naft Safid to the Eocene or Cretaceous though one was projected.

Production: Although gas was first found in 1934, commercial production of oil from Naft Safid did not begin until May 1945 when it was at a rate of 11,400 barrels per day. It had reached a level of 25,000 barrels per day at the end of 1950. The crude oil is of good quality (A.P.I. gravity 35.4°) and resembles Lali crude closely, though its sulphur content of 1.5% is higher. Cumulative production to the time of nationalization was 35 million barrels. The number of wells drilled was 23, of which 6 were producing at the time, and 5 others were oil wells but not on production.

(e) HAFT KEL. (Fig. 7 —Cross Section.)

Position: The Haft Kel field lies on a parallel line of folding to Masjid-i-Sulaiman, some 35 miles southsoutheast of the latter.

Surface Geology: Haft Kel is a 25 mile long asymmetrical fold in Upper Fars, Middle Fars and Lower Fars rocks. The Lower Fars covers a wide expanse on the southwest side of the anticline and is believed to be in the form of a thrust sheet overlying the northeast flank of an Upper Fars/Bakhtiari syncline. This syncline is completely obscured by the alluvium of the Tigris/Euphrates Plain against which the Lower Fars thrust sheet ends abruptly.

Oil Indications: Surface indications are few; there is a small thick oil show, a patch of bitumen-impregnated gypsum and a sulphur spring on the southeast pitching end of the structure; and an active gas escape with 'gach-i-turush' in the crestal area. All these are in Lower Fars rocks.

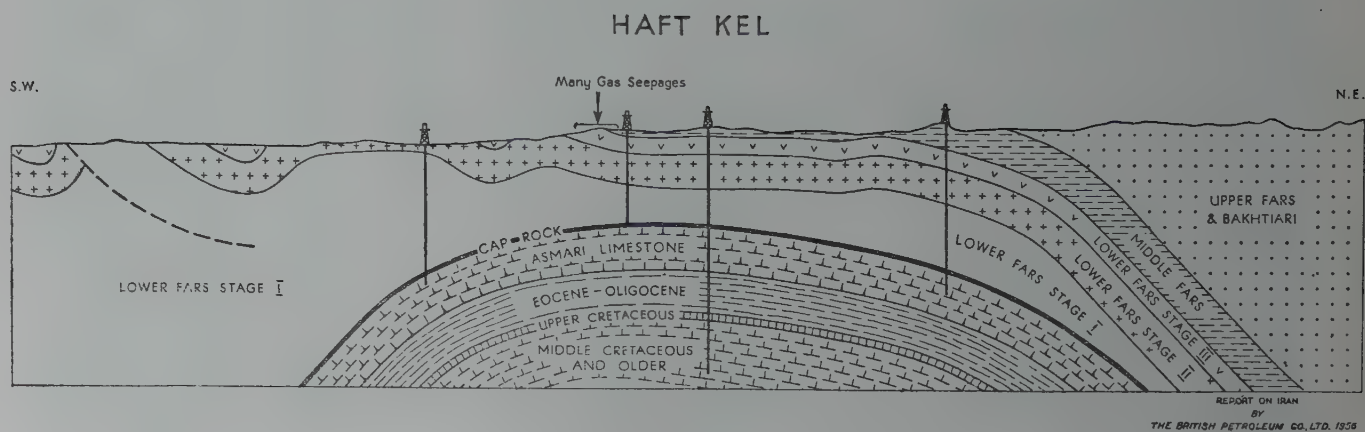

Figure 7. Cross-section Haft Kel.

History: The earliest exploration work in this part of the foothills had been concentrated in the Mamatain area to the southeast, where large active oil and gas seepages attracted attention before the less obvious oil indications of Haft Kel. Drilling was undertaken at Mamatain in 1905-07 and again in 1921-24, when the Asmari was found to be water-bearing. In order to ascertain whether there was a saddle between Mamatain and Haft Kel a 1-inch survey was undertaken in 1923-24, which indicated an Asmari culmination at Maidan-i-Gogird. Two locations were recommended and drilling began in 1926. After No. 1 had been abandoned in Lower Fars, No. 2 reached the Asmari limestone in February 1928 and became the discovery well of the field. Commercial production began in 1929, at an initial rate of 5,500 barrels per day.

In order to develop reserves quickly to supplement the 20-year Masjid-i-Sulaiman field, locations were made in the vicinity of the discovery, which was then found to be on the southeast pitching end of the Asmari anticline. Subsequent drilling was carried out by steps along both flanks, the locations being assisted by a seismic refraction line and arc survey. It was not until later (1930) that the significance of the active 'gach-i-turush' at Maidan-i-Gogird was understood, when it was found to mark the position of the central gas cap, of which there were originally three; two of these have now merged as a result of production. Development continued until 1946, and peak production (216,000 barrels per day) was reached in mid-1948.

Underground Structure: The Haft Kel Asmari structure forms the central member of the long anticline running from Mamatain in the southwest, from which Haft Kel is separated by a saddle, to Naft Safid in the northwest.

The structure is fairly symmetrical, though still slightly steeper on the southwest than on the northeast. There is considerable disharmony between the Asmari and its Fars cover rocks but less than at Masjid-i-Sulaiman or Lali. Attenuation in Stage 1 of the Lower Fars is also less. The field is 17 miles long by 2¾ miles wide, and has a minimum depth of cover of 1,900 feet. The thickness of the reservoir is fairly uniform, about 900 feet. It has two separate domes, both with gas caps. The southeastern dome is shallow, but the northwestern dome lies some 1,200 feet deeper.

Reservoir: The Asmari Limestone has an average thickness of about 900 feet, of which the upper 500 feet is more porous than the remainder, having an average porosity of 9.5%, the average for the whole thickness being about 7.4%. Fissuring is extensive throughout but somewhat restricted at the extreme pitching ends.

Only 1 well has drilled through the Eocene to the Cretaceous. It was located on the crest maximum, and found the Eocene/Upper Cretaceous interval thinner (only 1,000 feet) than at Masjid-i-Sulaiman. The Eocene was oil-bearing but the Middle Cretaceous limestone, though showing plentiful oil traces, was water-bearing, as at Masjid-i-Sulaiman.

Production: As already stated, fissuring and porosity in the Asmari Limestone are good, and prolific production has been obtained from all wells. The field has produced over 1,000 million barrels of oil, and before the shutdown in 1951 was producing at a rate of approximately 170,000 barrels per day. The oil is of good quality (A.P.I. gravity 37.8°), and with slightly higher sulphur content (1.22% by weight) than Masjid-i-Sulaiman. Since production began in 1929 the gas cap has expanded considerably, but, unlike Masjid-i-Sulaiman, the oil/water level has risen too, though the rise is not equal to that of a competent water-drive. The Eocene and Cretaceous reservoirs at Haft Kel are in fluid connection with the Asmari and are drained by production from the Asmari. It is considered that oil/water level was originally at the same elevation in the Asmari, Eocene and Cretaceous. The Eocene reservoir is of little importance because of its extremely low porosity.

(f) AGHA JARI. (Fig. 8 —Cross Section).

Position: The Agha Jari field lies on the edge of the folded foothills belt, some 80 miles east of Abadan Island and 40 miles from the port of Bandar Mashur. The thrust front of the fold rises some 600 feet abruptly out of the alluvium of the Persian Gulf Plain.

Surface Geology: Agha Jari is a 30-mile long, asymmetrical, faulted anticline in Upper Fars and Middle Fars, with Lower Fars evaporites exposed in its crestal culmination. Going northwestwards across the structure there is a sharp fold forming a topographic high to the northwest of the thrust fault (frontal pucker) followed by an undulating medial plain of Middle and Upper Fars, then a bold scarp of red

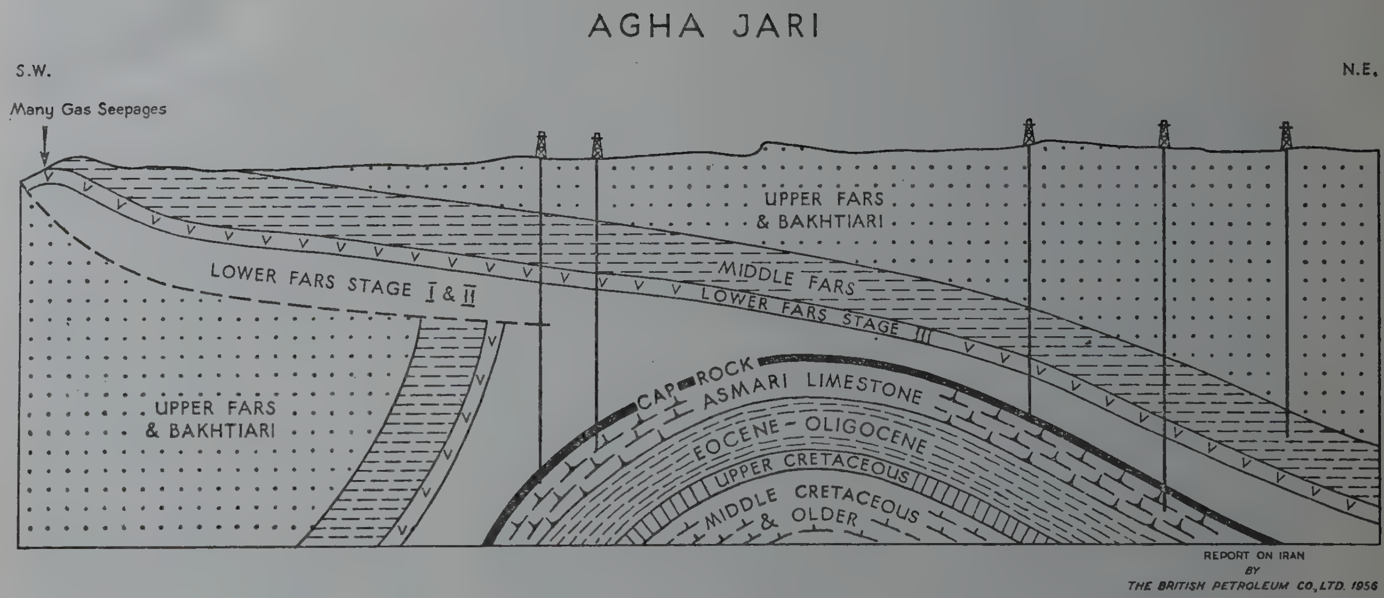

Figure 8. Cross-section Agha Jari.

sandstones and marls of Lower Bakhtiaris in a line of high hills which overlie the northeast flank of the underground structure (Ion, Elder & Pedder, 1951).

Oil Indications: Strong gas seepages with 'gach-i-turush' occur along the frontal pucker close to the thrust fault for a distance of 6 miles, including an area of spontaneous combustion, where the Fars rocks have been indurated and altered with, in places, the formation of aegirine-augite. This occurrence has been described in the literature, first by McLintock, 1932, and later by Ion, et al, 1951.

History: The Agha Jari area was first examined in 1914. Later, in 1925, when a theory was held that the 'lagoonal facies' of the Asmari reservoir was necessary for oil accumulation (Richardson, 1924; Lees, 1938), the area was favourably viewed. It was consequently mapped in that year, with the Pazanun area, and it was decided to drill exploration wells on both units. Drilling began in November 1926 at Agha Jari, the first well being located about 1 mile northeast of the frontal pucker. The size of the thrust fault was not then known, and consequently insufficient allowance was made for the displacement. The help of a geophysical reflection survey to define the fault was sought but no definite results were obtained. The well, after reaching Lower Fars at 915 feet, passed at 2,700 feet into red sandstones and marls of Lower Bakhtiari/Upper Fars age.

It was not until 1936 after further geological work that the structure was drilled again. No. 2 well, located some 2½ miles across the strike, found the Asmari limestone to be gas-bearing. It thus became the discovery well. The third well, located still further to the northeast across the strike, reached the oil-column on the northeast flank. By the beginning of the war two potential producers had been completed on the same flank, and two were drilling, but drilling activities were suspended until 1943. To provide more oil to the Abadan Refinery for the war effort in the Far East development of the Agha Jari field was then decided on; by June 1945 11 wells had been drilled, of which six were potential producers, 2 wells were drilling, and the field was on production from 3 wells. Its initial (end 1944) rate of production was 57,000 barrels per day.

In 1945 the first large-scale seismic refraction survey defined the axis of the structure in the Middle Cretaceous Limestone, which assisted the location of subsequent development wells.

Intensive development continued until nationalisation in 1951, and has been proceeding again since 1954.

Underground structure: The underground Asmari structure is a typical Iranian anticline, long, narrow and running northwest-southeast. It is more steeply folded on the southwest than on the northeast, especially towards the southeastern end where the dip on the southwest flank approaches the vertical. The full extent of the oil-bearing area is not yet known, but of the total length only 16 miles had been drilled by August 1951.

The marked disharmony between the Asmari Limestone and its cover rocks, the attenuation of the Lower Fars over the underground crest, and the complex tectonic history of the fold, resulting in the strong thrusting of the cover rocks to the southwest, have been discussed in detail by Ion et al (op. cit.). The structural relations of the Agha Jari fold to the northwest and to the southeast, where it is separated from the Pazanun structure by a deep saddle, which however, shows no surface closure in the Fars rocks, are also explained in this paper.

Reservoir: The thickness of the Asmari Limestone in the Agha Jari field is not known, as no well has yet penetrated right through it. Its outstanding feature is the very free fissure connection, illustrated by the large productions obtained from wells drilled only 20 feet into the limestone (up to 40,000 barrels per day). Moreover, good lateral connection exists even across the crest, witness the equal fall in datum pressure of 2 observation wells 7½ miles apart. The porosity of the reservoir, on the evidence of wells so far drilled, is not particularly high, but they have only penetrated the upper part, so that conditions in the lower Asmari are not known. Estimated average porosity is 7.6%. The fact that there is less development of marl in the lower Asmari of the surrounding ('Southern') area leads to the expectation that the porosity may be more uniform throughout the Asmari at Agha Jari than in the 'Central' area (Masjid-i-Sulaiman and Haft Kel), where the lower Asmari has a very low porosity.

The reservoir has two gas domes. No well has yet penetrated the oil/water level, and it is not known whether a water drive is in operation.

Anomalous accumulations of gas, condensate and brine have been found in Lower Fars Stage 3 on the southwest flank, the reason for which have been discussed in Ion et al, 1951.

Production: Up to August 1951, 34 wells had been drilled, from 20 of which production has been taken. The A.P.I. gravity of the crude oil is 34.6°, with 1.42% sulphur. Cumulative production of the field to August 1951 was 428 million barrels (daily average at this time 350,000 barrels per day). During the 3½ years shutdowm July 1951-November 1954, 30 million barrels were produced (Graham, Hetherington, Old & Tuman, 1955).

(g) PAZANUN. (Fig. 9 —Cross Section).

Position: The field lies 15 miles southeast of Agha Jari on the same anticlinal axis, and separated from it by a deep saddle. The fold forms part of the Khalafabad-Zaidun range which continues through Agha Jari, but is here topographically higher than at the latter.

Surface Geology: The surface fold is long, narrow and asymmetric. Lower Fars rocks are exposed on the southwest flank with Middle and Upper Fars and Bakhtiari on the northeast. As at Agha Jari there is a thrust fault disrupting the southwest flank. At one point the fold has been so deeply eroded that the vertical and overturned sub-thrust Upper and Middle Fars beds are exposed.

Oil Indications: There are no gas seepages at Pazanun, a fact which can be attributed to the great thickness of Lower Fars evaporites. The lack of seepages may have resulted in Pazanun's greater gas column compared with other southwest Iranian fields.

History: The early history of the Pazanun area has been described with that of Agha Jari. The first well began drilling in 1926 but was suspended in 1930 without reaching the Asmari, as it was thought to have been located too far to the southwest of the Asmari axis. No. 2 was begun in 1935 and the following year became the discovery well when it struck the gas cap. It was located 1 mile east across the strike from No. 1, and found the Asmari limestone a short distance southwest of the crest. No. 3 was located still further across the strike but nevertheless also struck the gas cap. The same result was obtained in No. 4 which began drilling in 1937 at a location further still across the strike and was completed in 1939. During the war all three gas wells were put on production to supply Abadan Refinery with condensate in order to help meet the heavy demand for aviation spirit.

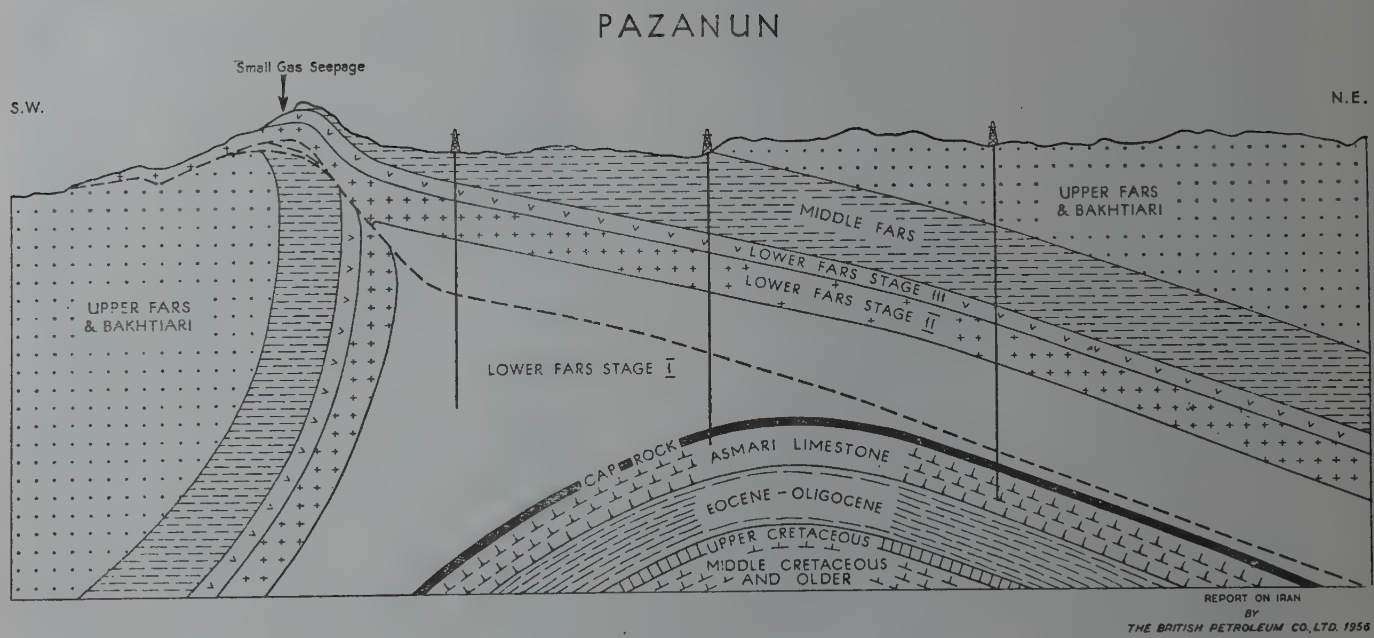

Figure 9. Cross-section Pazanun.

This demand ceased at the beginning of 1945 and thereafter only small quantities were produced for local purposes until August 1946, when all the wells were mudded off. Since the war further development of the Pazanun field was postponed in favour of Agha Jari.

Underground Structure: As only 3 wells, all at the northwest end, have been drilled into the Asmari Limestone, its structure is still unknown. 700 feet of Asmari limestone have so far been penetrated but its total thickness is not yet known. The caprock is thicker than in the central area and has an average thickness of 120 feet. There is a great thickness of saliferous Lower Fars Stage 1, particularly in the crestal area where No. 2 well proved nearly 3,000 feet. The crest maximum appears to rise to approximately the same elevation as Agha Jari, the minimum depth to the reservoir so far drilled being 5,500 feet.

Reservoir: All three wells encountered high pressure gas. The gas column already proved is 1,589 feet. It is possible that an oil column underlies the gas. The average porosity of the Asmari Limestone by visual examination is estimated at 7% in the top 700 feet.

Production: As stated above, condensate was produced from all 3 wells from 1943-1946, after which the wells were mudded off. Altogether about 126,000 m.c.ft. of gas and 2.26 h.m.g. of condensate was produced at a condensate/gas ratio of about 1.8 gallons/1,000 cu.ft. (Lees, 1953).

(h) GACH SARAN (formerly Gach-i-Qaraghuli) (Figure 10 —Cross Section).

Position: Gach Saran is the most southerly of the producing fields, and lies 165 miles southeast of Masjid-i-Sulaiman, near the border of the Fars province. During the initial exploration period access to the area was from Mishun, reached from Ganaweh on the Persian Gulf coast, 60 miles to the southwest; the present motor-road from Behbehan was completed in 1936.

Surface Geology: The oilfield underlies an area of Lower Fars gypsum and marls, much thrust-faulted, with a Middle Fars syncline directly overlying the Asmari crest. The field, which is the highest, topographically, in Iran, is dominated to the northeast by the hugh pre-Asmari mass of Kuh-i-Khumi, bordered by a wide gravel fan plain.

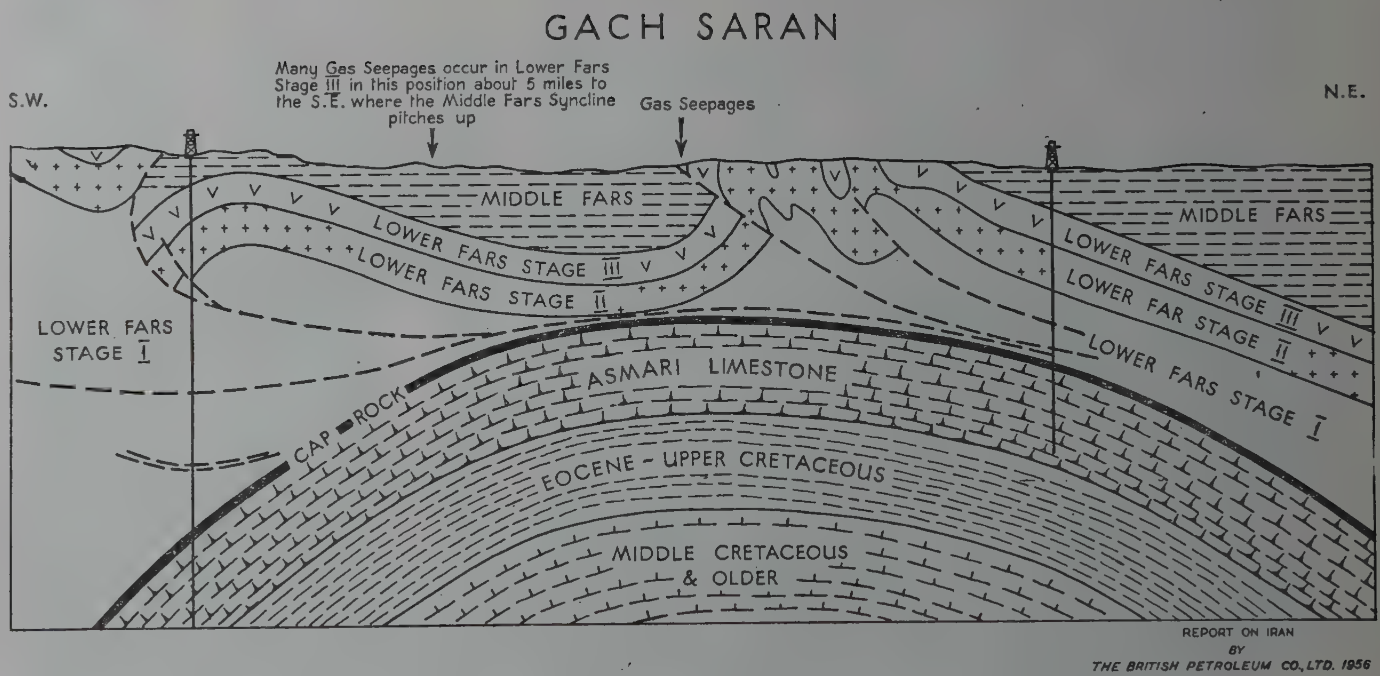

Figure 10. Cross-section Gach Saran.

The Lower Fars area is overlain by residual synclines of Middle and Upper Fars and Bakhtiari conglomerates, which form prominent features in the landscape, particularly the strong limestones of the Middle Fars.

Oil Indications: Indications of hydrocarbons are numerous, including oil seepages with dark brown/black oil, and several, 'gach-i-turush' occurrences, some with secondary limestone and aragonite over the crestal area. There is also an occurrence of burnt rocks off the southeast end of one of the Fars synclines overlying the Asmari crest.

History: The existence of these and other large oil seepages around Mishun drew attention to the area, which was surveyed in 1921-22. Two synclines were chosen for testing, Sulabadar and Chillingar, and exploration drilling began in 1923. Sulabadar proved dry and it was then realised that the small exposure of Asmari limestone at its northwest pitching end must have drained the whole structure —"a barrel with the bung out". Two wells were also drilled on the Chillingar structure between 1923 and 1925, both of which found some oil, but in non-commercial quantity. This is the "small oilfield discovered, but not produced" listed earlier as (i) (see p. 39).

After this, further geological examination of the Southern Area turned attention to the Gach Saran area, then called Gach-i-Qaraghuli, and a detailed geological survey of it was made in 1925. The choice of Gach Saran was partly based on two hypotheses which have since proved of doubtful value, the first being its favourable position for finding the Asmari limestone in the lagoonal facies, which was then regarded by some geologists as a pre-requisite for oil generation and accumulation in Iran, and the second being the expectation that a flat plain of Lower Fars would overlie the Asmari crest, on the analogy of the central 'maidan' of Masjid-i-Sulaiman.

Two wells were accordingly located on the plain and drilling began in 1927, but both were abandoned while still in Stage 1 of the Lower Fars. A third well, about 1 mile northeast of No. 2, began drilling in January 1928 and at the end of that year, blew out, having encountered a strong flow of oil in the caprock. It was mudded off and suspended until 1937, when it was deepened into the Asmari limestone, where it gave an initial production of 26,000 barrels per day. No. 4, about ¾ mile northwest of No. 3, was also suspended, after meeting gas

shows in the caprock, until 1940 when it was deepened into the Asmari as a gas observation well. No. 5 had been suspended in Lower Fars in 1930 when, owing to the worldwide decrease in oil demand, the area was closed down.

Operations were resumed in 1936 when No. 6 started drilling and, in March 1937, found the oil-column in the Asmari. In 1936 further geological work had been carried out, together with a seismic refraction survey. These surveys gave a much clearer picture of the Asmari structure and enabled well locations to be made with more confidence at a wider spacing more in keeping with the size of the field. Drilling continued until 1940, when once again development work was suspended. Commercial production then began. Since then, apart from an attempt in 1948 to deepen No. 6 well to the Cretaceous, there have been no drilling operations, owing to the preferential development of Agha Jari with its better quality oil. The A.P.I. gravity of Gach Saran oil is 32.0°, with sulphur 1.6%.

Underground Structure: The Asmari structure is a large, broad anticline with its axis running, as usual, northwest-southeast. It is fairly asymmetrically folded, except at the southeast end. It has dips up to 30° on the southwest flank, and up to 25° on the northeast. The plunge at the northwestern and southeastern ends is thought to be about 12°. There is complete disharmony between the surface structure and the Asmari limestone, with which the Cap Rock, stratigraphically part of the Lower Fars, is folded conformably. There are thick accumulations of Lower Fars on either side of the Asmari axis, made up of repetitions of Stage 1 mudstones (including polybituminous marls) and salt. Knowledge of the size of the field is incomplete but the proved area is 14 miles by 4 miles. There is a small gas-cap in the crest of the main anticline and a smaller one in a subsidiary dome to the southeast. The minimum depth of cover to the Asmari is about 2,500 feet.

Reservoir: The Asmari series differs from that of the Central Area fields in that it shows a poorer development of anhydrites and marls. At Gach Saran the lower part is mainly of massive limestones.

The Asmari limestone itself is thicker than in the more northerly fields, about 1,500 feet, and the basal part being mainly limestone, forms a better reservoir. The overall porosity of the Asmari is estimated at 7.7%, but the significant feature is the high proportion of total

pore space which is made up of large pores. The degree of fissuring, however, is variable, and not as uniformly good as Agha Jari or Haft Kel.

Production: Though discovered in 1928, for the various reasons outlined above, the field did not go on to commercial production until 1940. 15 wells have been drilled altogether but production between 1940 and 1951 was never from more than 4 wells at any one time. The small offtake from this, the largest of the Iranian reservoirs, is explained by the quality of the crude oil, which has a higher sulphur (1.6% weight) and asphaltene content than that from the other fields.

Only 2 wells have drilled below the Asmari limestone in this field, neither of which has penetrated more than the top of the Eocene.

Production in 1950 was at a rate of 42,000 barrels per day, and cumulative production of the field to July 1951 was 131 million barrels.

(j) KUH-I-MUND.

Position: Kuh-i-Mund lies over 100 miles south of Gach Saran and extends for 60 miles along the Persian Gulf coast southeast of Bushire. It is a gentle and almost symmetrical anticline, reaching a height of about 2,000 feet and forming a prominent topographical feature, surrounded as it is by flat, low-lying country. The general trend of the range is more nearly northnorthwest to southsoutheast than the customary northwest to southeast trend further north. Geologically the anticline lies within the Cambrian salt dome province of Fars and Laristan.

Surface Geology: The anticline is in Upper, Middle and Lower Fars rocks, in which faulting is confined to a few small normal faults. There is a sudden swing in the axis which runs southeast to northwest in the southern two-thirds and almost north to south in the northern one third.

Oil Indications: A small 'gach-i-turush' occurs on the crest.

History: The area was first examined and roughly mapped in part in 1919, though it had been visited earlier and noted. Instrumental sections were measured in 1925 and the structure was mapped on a one-inch scale in 1926. Uncertainty prevailed regarding the depth at which the Asmari limestone might be found in Kuh-i-Mund, and in

what facies it would occur, but the decision to drill it was taken in 1929 on the strength of its structural excellence and the possibility of striking oil in lower horizons. A location was chosen in 1930 and a detailed geological survey was made of the neighbouring structures to facilitate correlation. Drilling began in January 1931 and continued to the Cretaceous. Shows of very heavy oil of about 5.0° A.P.I. gravity were met in the Eocene and the Cretaceous limestones, but on test the well would not flow, and was abandoned at a depth of 3,837 feet in 1932.

The sequence drilled in the well differed considerably in lithology and thicknesses from equivalent sections exposed in the neighbouring mountains. The Asmari, as a limestone series, has virtually disappeared in Kuh-i-Mund. Overlying an 80-foot band of limestone of undoubted Oligocene age there are 800 feet of interbedded limestones, anhydrites and marls, both grey and red; much of this interval, from the faunal content, must be the time equivalent of the Asmari of other areas, but some of it also must belong to the Lower Fars.

Various explanations have been put forward to explain the quality of the crude oil found in Kuh-i-Mund No. 1 and the fact that the well would not flow (e.g. loss of light ends from the oil through erosion of the structure; lack of hydrostatic pressure due to topographic elevation; etc.) but none has been generally accepted.

DEVELOPMENT AND EXPLORATION CONDITIONS IN THE MAIN FIELDS

The difficulties of exploration and development which have beset the southwest Iranian fields are in most cases common to them all. There are some conditions which apply only to one or other of the individual fields, and these have been mentioned in the chapters on the stratigraphy, structure and history of the oilfields.

a) *Transport and Services.*

In the early days of exploration the most serious difficulty was transport. Few roads existed and no railways; the country was large, distances long, and the terrain hilly if not mountainous and for the most part unmapped. By 1951 many miles of road had been built by the Company and air transport was extensively used. The example of the hindrance to the development of Lali from lack of transport over the Karun has already been cited.

A factor which in the past considerably slowed down the development of the Iranian fields, and one which is not always appreciated, is that all basic services, such as housing, water supply, power, and so on, as well as amenities for the staff, had to be provided *ab initio* by the operating company. This, as in the case of transport, frequently entailed the carrying out of major engineering projects before the full technical development of an oilfield with its production plant, pipelines, etc., was possible. Before Gach Saran was drilled, for example, a tortuous road 80 miles long from the Persian Gulf Coast had to be constructed.

Some idea of the scope of transport and background services which had to be provided 'from scratch' to enable drilling and, later, development to proceed can be gained from a book by Williamson "In a Persian Oilfield" (1930).

b) *Drilling.*

I. The difficulties experienced in drilling in the Iranian fields are well known, the chief of these being the *high pressures* met with in the Iranian reservoirs; it was indeed fortunate that discovery of some of the high pressure gas domes was not made until rotary drilling was adopted. The methods of overcoming these high pressures have been described by Scott, 1933; Seamark, 1933; Lane, 1949; P. W. Cooke, 1955. The difficulties of this nature experienced in the Agha Jari field have already been mentioned (Ion, et al, 1951).

II. Other drilling difficulties are caused by *swelling or caving of marls* in the Lower Fars where there is faulting or where for other reasons the marls are unstable. The technique of controlling these occurrences by the use of heavy brine-base, low water-loss muds has been discussed by Strong, 1933, 1938, and P. W. Cooke, 1955.

c) *Geological.*

As far as *geological* conditions in the oilfields are concerned, enough has been said in describing the individual oilfields to show the growth of accurate knowledge of structure and stratigraphy over the years. Once the identity of the Asmari limestone reservoir was established the main hindrances to accurate correlation were always (1) the lack of knowledge of the original thickness of the Lower Fars Stage I evaporites and (2) thickness changes due to their erratic

tectonic behaviour. These hindrances have been largely overcome by two methods of *correlation* —one by micropetrographical means i.e. the identification of mineral inclusions in the anhydrite beds (Strong, 1937) and by the texture of the anhydrite itself, and one by identification of foraminiferal faunules worked out by W. Kitchin in the north and by F.D.S. Richardson in the south (Lees, 1953). The geological problems involved in drilling control are unsuited for the electric logging technique usually used elsewhere.

d) *Geophysical.*

Once the structural anomaly between the oil reservoir and its overburden became apparent (e.g. in Gach Saran and Lali where synclines rest directly on top of underground anticlines), *geophysical methods* were used increasingly to assist in locating the underground structures and later to define the structures in greater detail for accurate well locating. In particular, the refraction arc method, developed by the (then) Anglo-Persian/Iranian Oil Company, was of great efficacy (Jones, J. H., 1933; Germain-Jones, D. T., 1951).

e) *Production.*

One condition, which has been of immense value in the development of the Iranian oilfields is the fact of '*unit operation*' (Comins, 1928; Southwell, 1933), which has enabled reservoir conditions to be studied at every stage, and the control of the reservoir for the most economic development of each field to be adopted. The first time unit scientific control was adopted for any oilfield was in the development of the Masjid-i-Sulaiman field.

EXPLORATION DRILLING, DEVELOPMENT DRILLING & PRODUCTION STATISTICS DURING LAST 10 YEARS

a) DRILLING 1945-55.

	Exploration			Development			Total		
Year	Wells Drilling	Wells Completed	Actual Footage Drilled	Wells Drilling	Wells Completed	Actual Footage Drilled	Wells Drilling	Wells Completed	Actual Footage Drilled
1945				15	6	35204	15	6	35204
1946				13	6	21354	13	6	21354
1947	1	—	4946	15	5	38401	16	5	43347
1948	1	1	1538	14	6	45806	15	7	47344
1949	2	1	13736	16	5	57656	18	6	71392
1950	3	—	10246	28	7	87131	31	7	97377
1951	3	—	12868	22	5	52366	25	5	65234
1952									
1953									
1954									
1955									

b) IRANIAN CRUDE OIL PRODUCTION *(in thousands of barrels)* 1945-55.

1945	130,526
1946	146,819
1947	154.998
1948	190,384
1949	204,712
1950	242,475
1951	127,600
1952	10,100
1953	9,800
1954	14,016
1955	116,382

(figures from 'World Oil' Forecast-Review issue 15.2.56.).

PETROLEUM EXPLORATION VOLUME

Survey Months

Year	Geological Surveys	Geophysical Surveys			Total
		Refraction	Reflection	Gravity	
1945	—	6	—	—	6
1946	1½	6	—	—	7½
1947	4	3	2	—	9
1948	10	11	6	—	27
1949	16	16	7½	—	39½
1950	20	13	8½	1½	43
1951	13	5	5	5	28
1952					
1953					
1954					
1955					

OIL AND GAS RESERVES

No authoritative contribution to the complex question of estimating oil reserves in the southwest Iranian limestone fields can be made in this compilation. A number of estimates of the proved oil reserves of Iran have been published, for instance the 'Oil and Gas Journal' of 26.12.55, gives a figure of 27,000 million barrels, but in no case has the method by which the estimate was made been adequately discussed.

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IRAQ

GEOLOGICAL OCCURRENCE OF OIL AND GAS IN IRAQ

By the Staff of Iraq Petroleum Co. Ltd.

SUMMARY

The producing territory falls naturally into North Iraq and Basrah Provinces, providing 75% and 25% of the annual 32.000,000 tons. [1]

The former includes the foothills [1] and plains between the Zagros mountains, the highlands of S.E. Anatolia, and the desert of western Iraq.

The sediments are mainly calcareous to evaporitic from Permian to Middle Miocene, clastics becoming dominant and widespread only in the younger Neogene.

Numerous anticlines form hill ranges. In some oil occurs in fractured and porous Middle Cretaceous dolomites, in some in Tertiary lagoonal, reef and forereef limestones. Some carry medium light oil with or without gas cap, others gas alone, and others heavy oil.

The Basrah Province boundaries are: east, the Zagros foothills region; south, the Persian Gulf; west and north, undefined.

Several large gently-folded anticlines have been found by geophysics. Salt domes occur rarely.

Lower and lower-Middle Cretaceous sand and shale complexes carry prolific oil. Above comes a calcareous regime with minor shale and evaporitics (Eocene). In late Eocene this regime ends, being overlain by clastic deposition which, except for the evaporitic Lower Fars phase (Lower Miocene) still continues.

Shallow oils are heavy, and gravity becomes progressively lighter with depth.

GEOGRAPHICAL DISTRIBUTION OF OIL AND GAS

This is shown on the maps (Plates I, II, III, IV).

Several concessions for exploration and development of oil and gas in Iraq have been granted to various Companies, viz:

[1] Excluding Khanaqin Oil Co. Ltd.

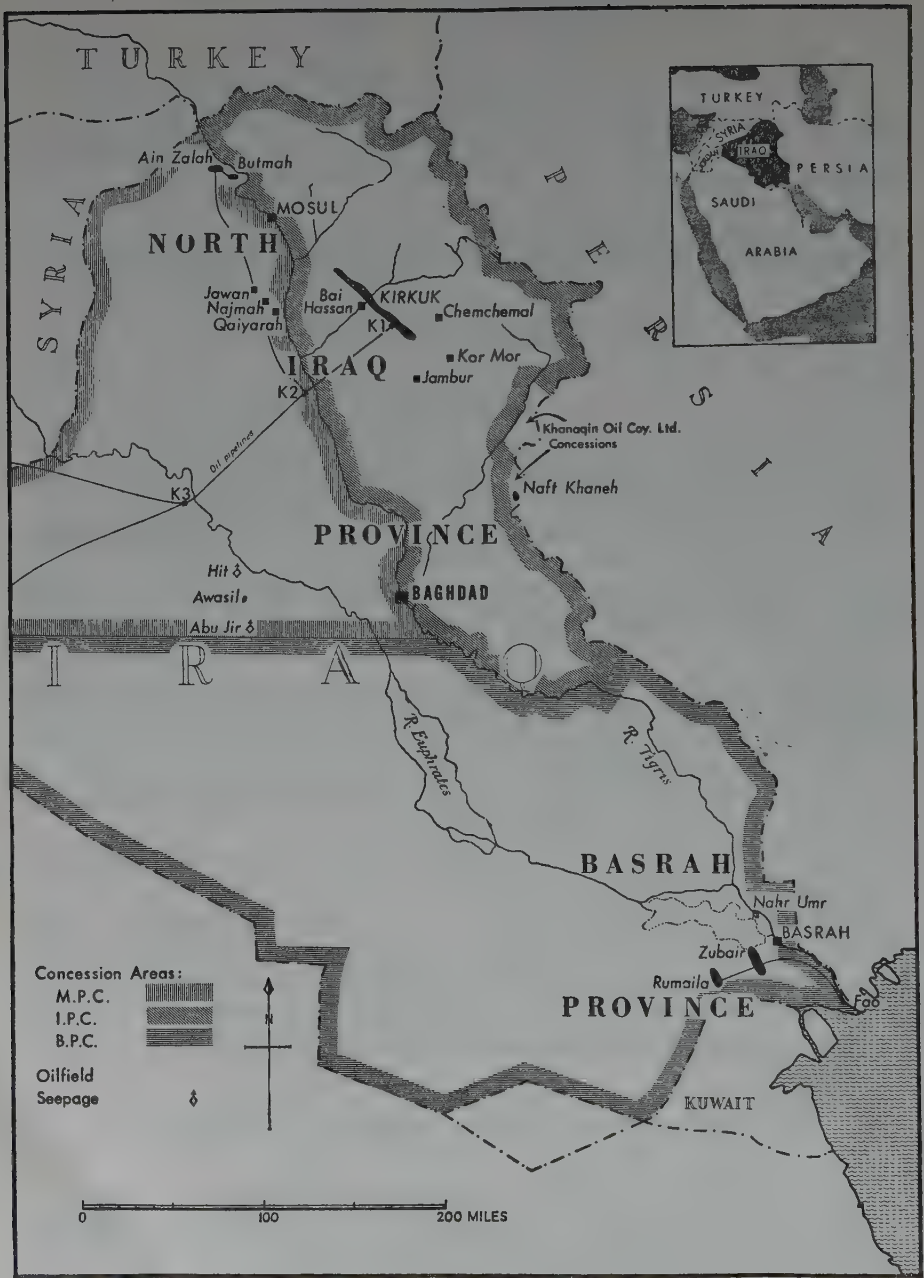

Plate I.—Key map showing localities.

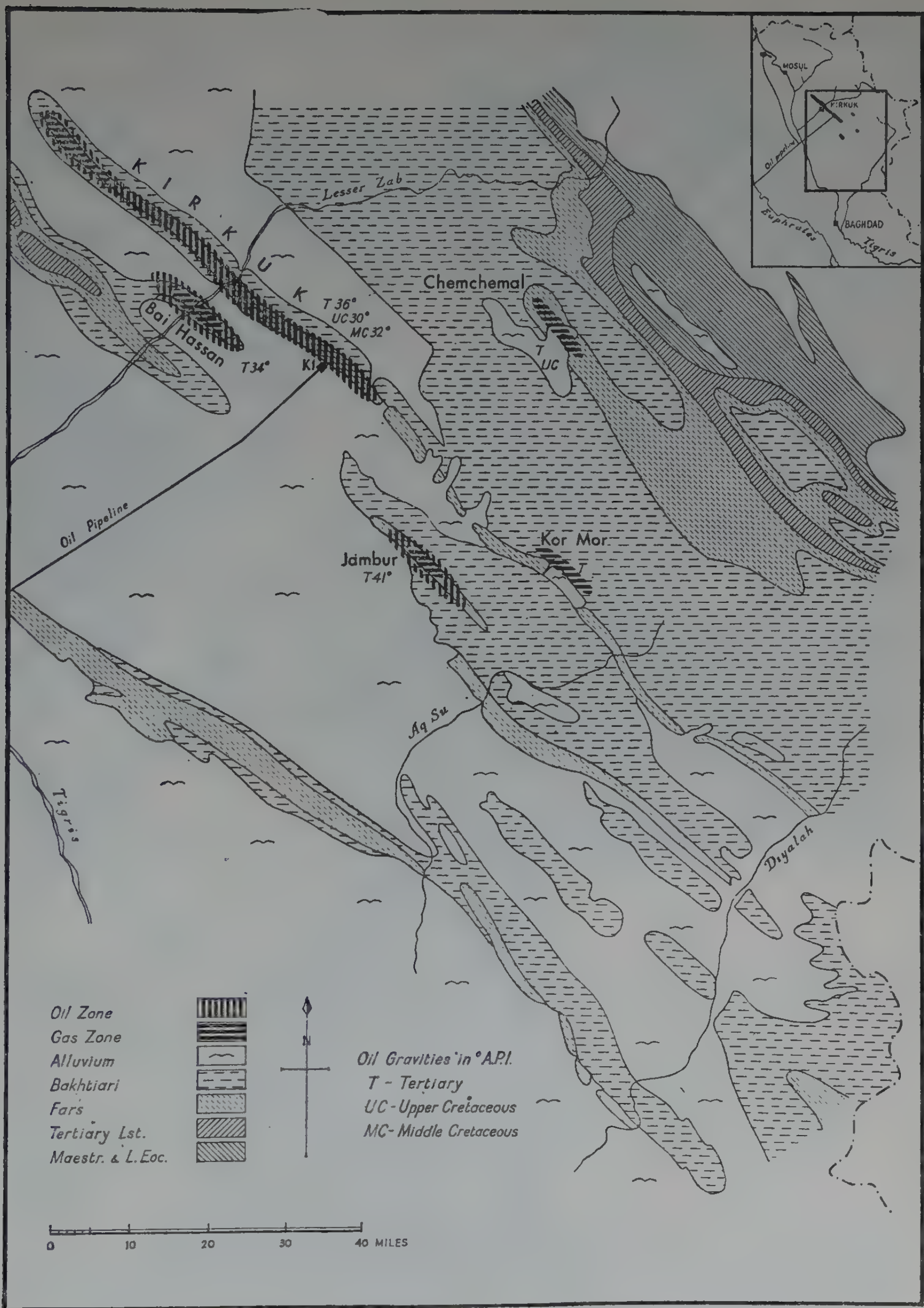

Plate II.—Geological map of I.P.C. concession showing fields and localities.

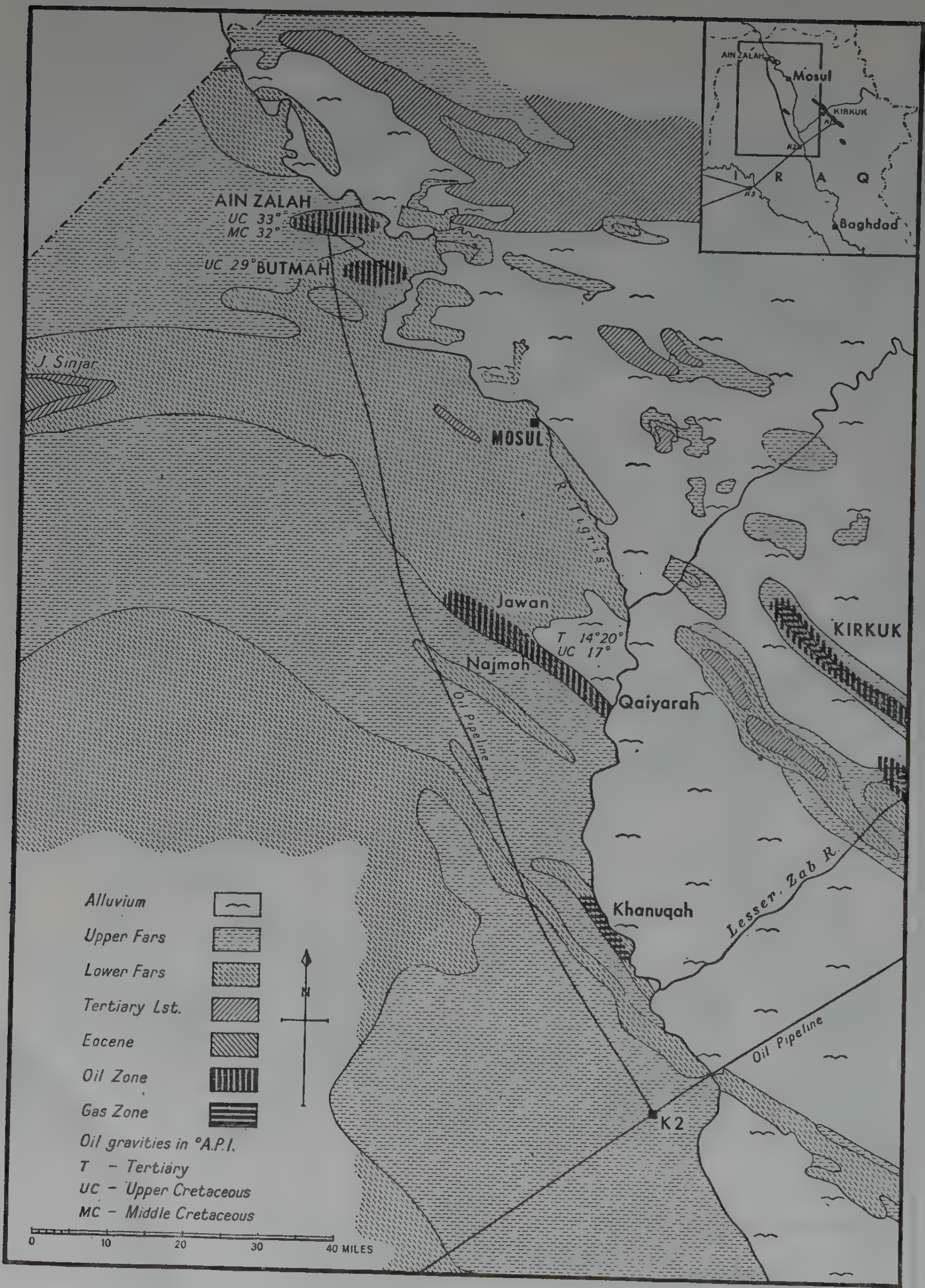

Plate III.—Geological map of M.P.C. concession showing fields and localities

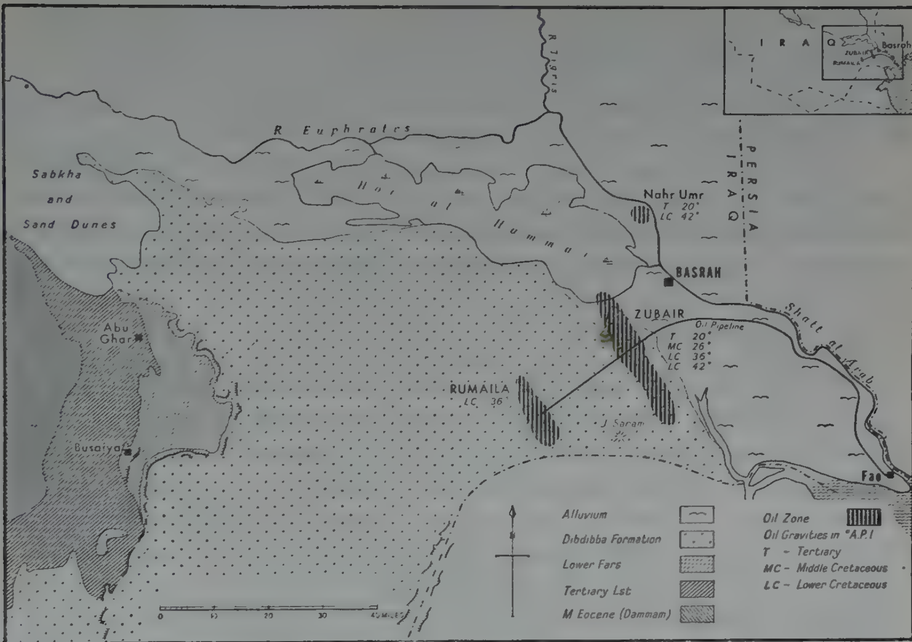

Plate IV.—Geological map of B.P.C. concession showing fields and localities.

1) Iraq Petroleum Company, Ltd. (I.P.C.): all of North Iraq east of the River Tigris as far south as Kut al Imara, and north of the Tigris and of its tributary the Chankuia Galal east of that town to the frontier of Persia; but excluding:

2) Khanaqin Oil Company, Ltd.: two concessions totalling some 1800 sq. km. (700 sq. miles) and lying along the Persian frontier, the larger just north of Khanaqin, the smaller, containing the Naft Khaneh oilfield, just south of that city. (Barber 1948, Longrigg 1954). Since these Concessions are the subject of a separate paper they will not be considered further here, and all data here given will be exclusive of Khanaqin Oil Company's territories.

3) Mosul Petroleum Company, Ltd. (M.P.C.): all of North Iraq west of the River Tigris as far south as Latitude 33° north, which parallel forms the southern boundary.

The oil and gas accumulations so far discovered by these Com-

panies within their respective territories are all considered on grounds of geological similarity to lie within a "NORTH IRAQ PROVINCE".

4) Basrah Petroleum Company, Ltd. (B.P.C.): all of Iraq south of the southern boundaries of concessions 1) and 3).

The accumulations of oil and gas so far discovered by the Basrah Petroleum Co. Ltd., are within 80 km. (50 miles) of Basrah City and so it has seemed appropriate to describe these by the term "BASRAH PROVINCE", rather than by a term of wider geographical implications.

NORTH IRAQ PROVINCE

It is not possible to sub-divide the Province according to age of reservoir because in several fields production may be obtained from more than one geological horizon. But as a generalisation it could be said that the Iraq Petroleum Company Concession is a region of oil accumulation in Tertiary reservoirs (Eocene to Middle Miocene): Kirkuk 36° API., Bai Hassan 34° API., Jambur 41° API., Naft Khaneh 42° API. To this should be added the large Qaiyarah-Najmah-Jawan structure in the M.P.C. Concession since main accumulation there, although of heavy sulphurous crude (14-20° API) and not commercially exploitable, is in Tertiary limestone (Oligocene to Middle Miocene).

Exceptions to the above, though minor, are the occurrence of wet gas in Upper Cretaceous fissured marly limestone at Chemchemal; of oil 30° API, and so somewhat heavier than the Tertiary oil, in the same formation at Kirkuk, where also 32° API oil occurs in Middle Cretaceous limestones and dolomites: and finally of heavy sulphurous crude (17° API), practically the same as that of the Tertiary reservoir, in Upper Cretaceous porous limestone of Qaiyarah-Najmah-Jawan.

As a further generalisation, the Mosul Petroleum Company Concession could be called a region of oil accumulation in Cretaceous reservoirs since there is production from fissured Upper Cretaceous marly limestone in Ain Zalah and Butmah (33° and 29° API); accumulation of heavy sulphurous oil (17° API) in Upper Cretaceous porous limestone at Qaiyarah-Najmah-Jawan; and production from Middle Cretaceous porous limestone and dolomite at Ain Zalah (32° API).

But an exception to this is the above-mentioned large accumulation of heavy oil in the Tertiary of Qaiyarah-Najmah-Jawan.

For similar reasons it is not possible to group the reservoirs by gravity of the crude, gas/oil ratio, sulphur content, sweet or sour oil, free gas, etc.

BASRAH PROVINCE

Again it is not possible to define distribution of oils either by geological age or by other characteristics.

Thus the Nahr Umr and Zubair structures contain very viscous sulphurous heavy oil (20° API) in the lowest beds of, and immediately below, the Lower Fars (Lower Miocene), the so-called "First Pay".

The Zubair field can produce medium oil (26° API) from limestones at the top of the Middle Cretaceous —the "Second Pay".

The Nahr Umr structure has light oil (42° API) in sands at the base of the Middle Cretaceous.

The Zubair and Rumaila fields produce light medium oil (36° API) from sands of the Lower Cretaceous (Zubair "Third Pay"), while Zubair also produces light oil (42° API) with a high gas/oil ratio from the lower part of the same sand/shale complex which in this field is separated off below a shale break —the "Fourth Pay".

HIT AREA

Although no commercial production is obtained, mention must be made of the very extensive seepages of thick heavy sulphurous oil, amounting to small lakes of asphalt, which occur over a length north to south of 40 km. (25 miles) from Hit on the Euphrates River to Abu Jir. These seepages occur in porous limestone of Lower to Middle Miocene age, and are supposed to be due to upward migration along buried north-south faults.

A well drilled before the war at Awasil in this vicinity found heavy oil (10° API) in sands at the base of the Middle Cretaceous (thus of similar age to those carrying oil at Nahr Umr), and in limestone streaks in anhydrite of probable Upper Jurassic age .

GEOLOGICAL DESCRIPTION OF PROVINCES

The cross sections (Plate V) show the regional structural relationships so far as known.

Topographically and tectonically Iraq may be subdivided into:

1) a strongly folded mountain belt to the east —the Zagros mountains— passing westwards into:
2) a foothill region containing individual folds (which form anticlinal traps and provide the productive oil and gas fields of the North Iraq Province); passing westwards into:
3) a region of great plains broken by long linear folds separated by very wide and apparently flat-bottomed synclines; passing westwards into:
4) flat country with occasional wide gentle swells (providing the structural traps of the oilfields in the Basrah Province).

In so far as structure is concerned these sub-divisions refer to post orogenetic conditions, before which the gentle basins and swells of sector 4) extended over the whole oilfield region.

STRATIGRAPHY AND TECTONICS

Basement of igneous or metamorphic rock is not exposed in the Zagros mountains of Iraq where the oldest beds are quartzites and shales relatively gently folded and without appreciable metamorphism, to which pre-Devonian (? Ordovician) age has been asigned (Henson, 1951; Baker, 1953).

Following these, after an inferred hiatus without angular unconformity, come black limestones and shales of Devonian to Lower Carboniferous age (Henson, 1951; Baker, 1953).

Above these, again with inferred hiatus but without angular unconformity, there are black limestones with thin shales of Upper Permian age, followed by a virtually continuous Triassic-Jurassic succession of fine-grained 'chemical' limestones with shales, anhydrites and dolomites, often fetid and highly bituminous in the upper part.

During the Upper Jurassic —Lower Cretaceous interval intermittent movements began which accentuated the pre-orogenetic basin and swell structure so that Cretaceous/Jurassic relationships vary from those of continuity and conformity to those of marked unconformity.

It was also in Lower Cretaceous time that the first signs of deformation on the NW-SE Zagros trend are recognisable in the stratigraphy of the oil field area (Dunnington, 1955). The sedimentation in this region reveals thereafter a greater diversity related to the inter-

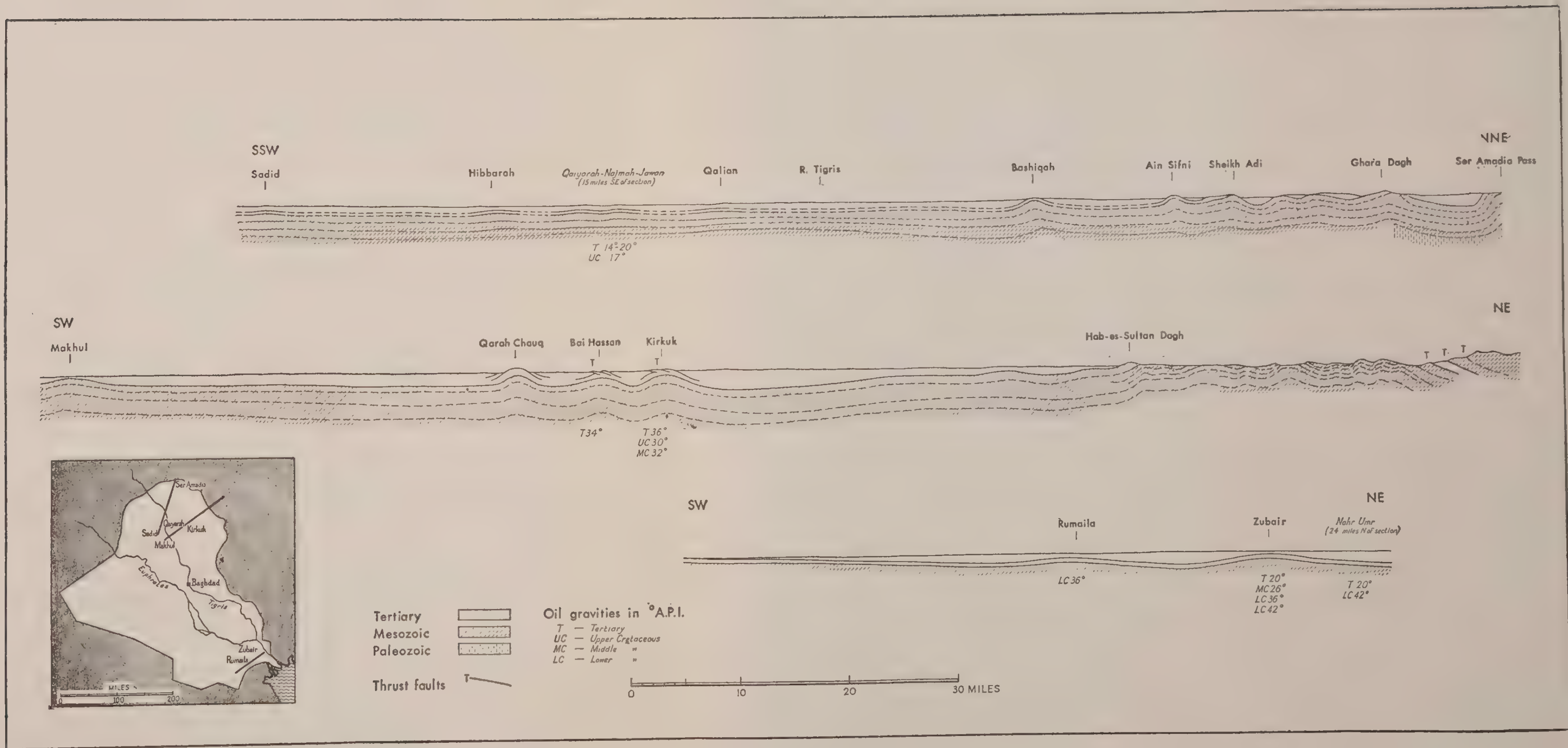

Plate V.—Regional structural cross sections.

play of these various movements and to the increasing effects of successive epeirogenetic oscillations which produced breaks of varying amplitude and extent.

Thus clastic deposits derived from the Arabian uplift predominate in the Lower-Middle Cretaceous of the foreland, and these pass eastwards into open sea deposits which consists mainly of globigerinal shales, marls and limestones in basinal environments, and of reef and shoal limestones in neritic environments. Similar conditions continued from Cretaceous to Lower Miocene times, with certain notable variations, viz:

a) In Upper Cretaceous-Palaeocene times important uplifts (associated with ophiolite extrusions) occurred to the NE, and erosion of these led to the deposition of a flysch facies in long relatively narrow NW-SE troughs to the SW. At the same time the first gentle folding occurred in the oilfield belt.

b) Less vigorous movements of the foreland shelf led to a restricted circulation of ocean water over certain areas where evaporites were deposited in Cretaceous (local), Lower Eocene, Oligocene, and Lower Miocene times.

Accentuation of these conditions b), then introduced the widespread 'Lower Fars' sedimentation of the Miocene (salt, anhydrites, limestones, and green and red mudstones) which continued until the southeastwards withdrawal of the sea set the stage for deposition of the continental 'Upper Fars' red beds, and the 'Bakhtiari' conglomerates and mudstones.

These clastic sediments, products of the culminating late Tertiary orogeny, were strongly thrust in the northeast and folded to the southwest, to produce and/or accentuate the anticlines of the oilfield belt, particular sectors of which may now be considered in more detail.

The general stratigraphy in the oilfields of the I.P.C. region (east of the River Tigris) is shown by the log of Kirkuk well 109 (Plate VI). It will be seen that clastics are practically absent, the oilfield belt having lain too far east to have received any sands or shales from Arabia in the Lower Cretaceous, and too far to the west to have received either Upper Cretaceous or Palaeocene flysch. Upper Fars and Bakhtiari clastics are present in great thickness in flanking synclines but do not appear in this crestal well (see Plate VIII).

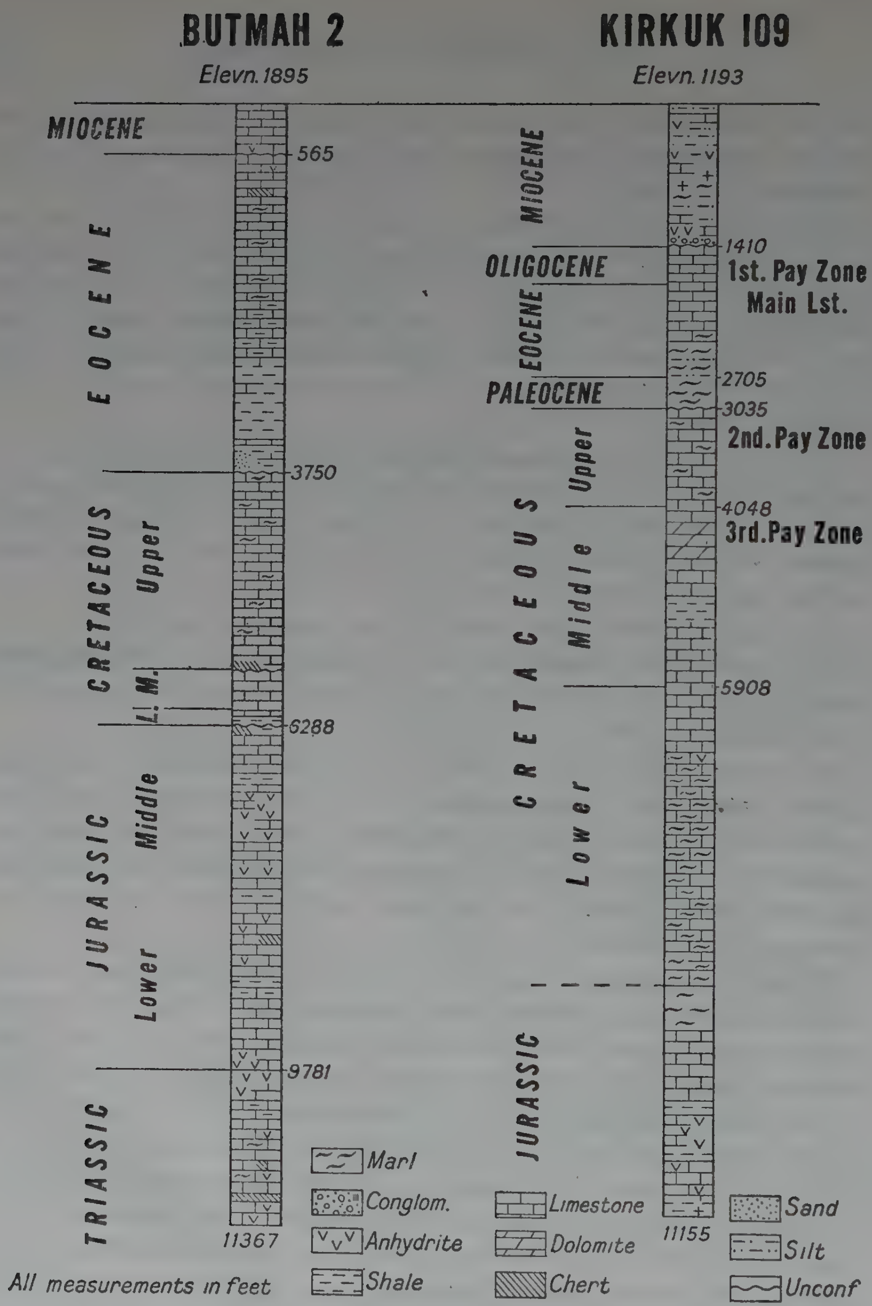

Plate VI.—Geological log of Kirkuk well No. 109: and of Butmah well No. 2.

The general tectonic setting of the M.P.C. area (west of the Tigris) is akin to that of the I.P.C. Concession but rather farther removed from the diastrophic region of Upper Cretaceous times as well as from the orogenetic zone of the Neogene. In the eastern part of the territory the Lower (and even part of the Middle) Cretaceous is cut out in varying amount over and eroded surface of Jurassic rocks, the Upper Jurassic being also mainly absent (Dunnington, 1955). The Upper Cretaceous and older Tertiary sediments show considerable variation in thickness. This situation is theoretically ascribed to the existence and vagaries of an old swell which progressively broke down into an horst-plateau and graben-basin region. The curiously interleaved strikes of the anticlines, their relatively short lengths, their surface expressions, and the apparently very flat and shallow synclines between them, are held to support this view and to deny that these folds are truly foothill buckling folds of the Zagros-cum-Turkish mountain systems.

The sediments here, shown by the log of Butmah No. 2 well (Plate VI), contain more limestone and less argillaceous beds than in the I.P.C. area. The Upper Cretaceous is almost entirely in globigerinal marly limestone facies. Fine clastics, shales with some fine sands, come in with the Palaeocene unconformably over slightly eroded Upper Cretaceous, followed by limestone deposition during the Eocene, on the northern structures; but these Eocene beds are generally lacking on the southern structures. The Oligocene is normally present but thinner in the south than in the north. The entire region was covered by the evaporites of the Lower Fars which were succeeded by a thin covering of Upper Fars. No Bakhtiari conglomerates and sands are known, nor are they thought to have been deposited here. Thus structurally there does not seem to be any deep basin(s) of sediment, nor much shale, marl or argillaceous limestone in this area.

In the Basrah Province the developed oilfields lie even further removed from the Upper Cretaceous diastrophism and the Neogene orogen. The Nahr Umr (?) salt dome seems to be in an intermediate position between the Basrah Province "Swell anticlines" and the true foothill folds of the Zagros (which in this geological province lie over the frontier in Iran).

The general stratigraphy is given by the log of Zubair well No. 30 (Plate VII). Some striking differences from the column in the North Iraq Province are revealed. Thus the upper part of the Lower

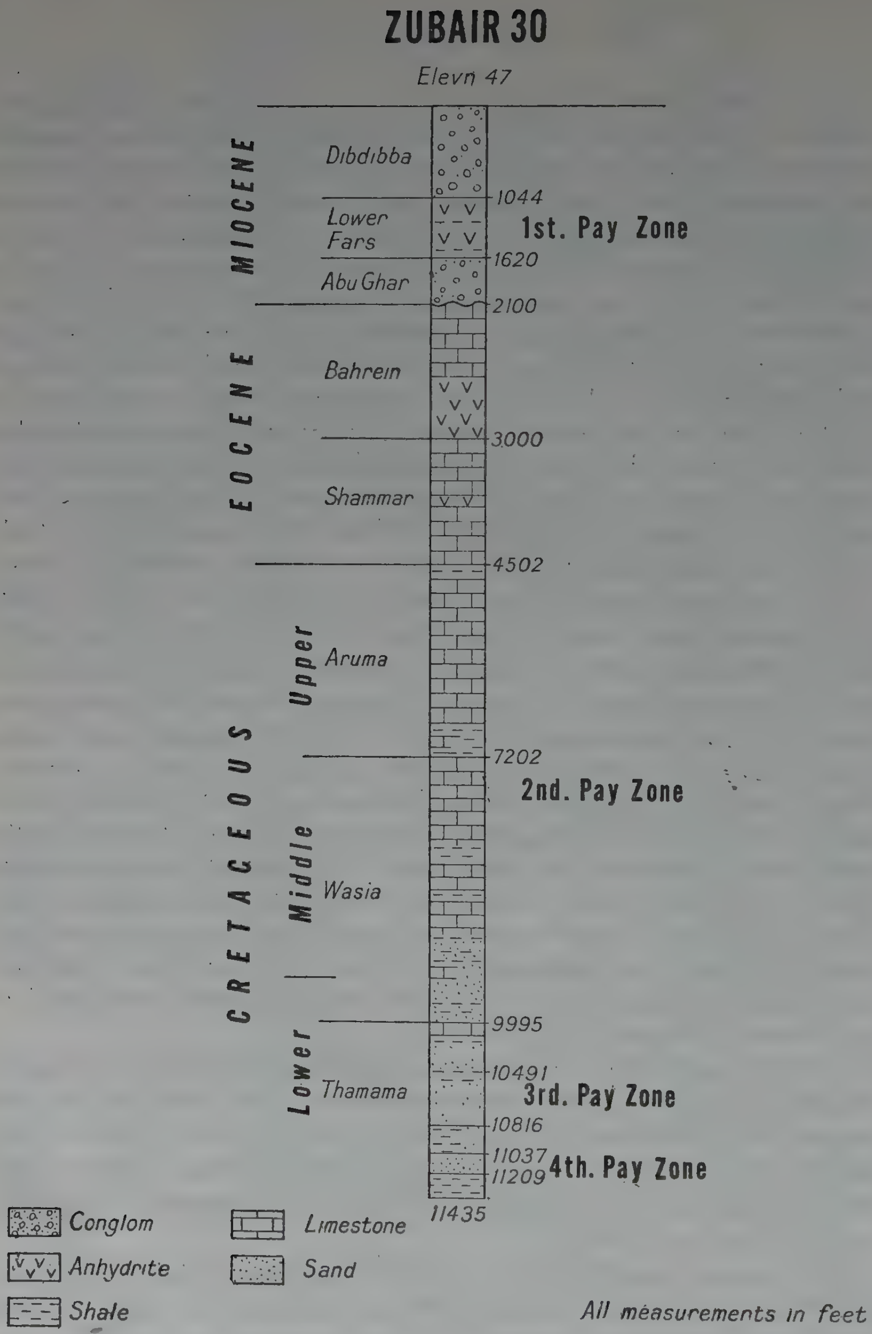

Plate VII.—Geological log of Zubair well No. 30.

Cretaceous (Zubair formation) and the lowest part of the Middle Cretaceous (Nahr Umr formation) are predominantly in sand and black shale development, the latter with minor limestone. These sands are the producing reservoirs. Above, the Middle and Upper Cretaceous section is dominantly limestone, organic and detrital, with relatively unimportant amounts of shale, though there is enough marl and marly shale to act as a seal and hold in the oil of the "Second Pay" in the Zubair field. The Eocene is mainly limestone, somewhat dolomitised, but there is often a considerable development of anhydrite —the Rus anhydrite— in the lower part. Higher, the beds become unfossiliferous and the Eocene is terminated by an (?) erosional unconformity. Overlying this comes a clastic sequence of sands, gravels, and gypseous clays of undetermined age, succeeded by the anhydrite, gypsum, mudstone and shelly limestone complex of the Lower Fars of Lower-Middle Miocene age. The youngest bedded rocks are again sands, gravels, gypseous silts etc., and are considered to range from Middle Miocene to Recent (alluvium). (Owen and Nasr, 1955).

The Hit region lies even further removed from the Neogene orogenetic zone than do the fields of the Basrah Province. But the general stratigraphy shows that it is more akin to that Province than to the north, the Lower and lowest-Middle Cretaceous (c.f. Zubair and Nahr Umr formations) being in a sand facies with minor shale, and of considerable thickness (about 455 m. or 1500 ft.).

GEOGRAPHICAL AND GEOLOGICAL DISTRIBUTION OF THE OIL AND GAS FIELDS IN EACH PROVINCE

This is shown on the accompanying maps Plates: II, III, IV.

STRATIGRAPHY AND STRUCTURE OF SOME IMPORTANT FIELDS IN EACH PROVINCE

I.P.C. CONCESSION —*Kirkuk field.*

A typical structural cross section (Plate VIII) and a longitudinal stratigraphical section (Plate IX) illustrate the nature of the field.

Happy coincidences have combined to make Kirkuk a marvel amongst oilfields. The structure developed very obliquely across a facies-trend of reef and shoal limestones ranging in age from Middle

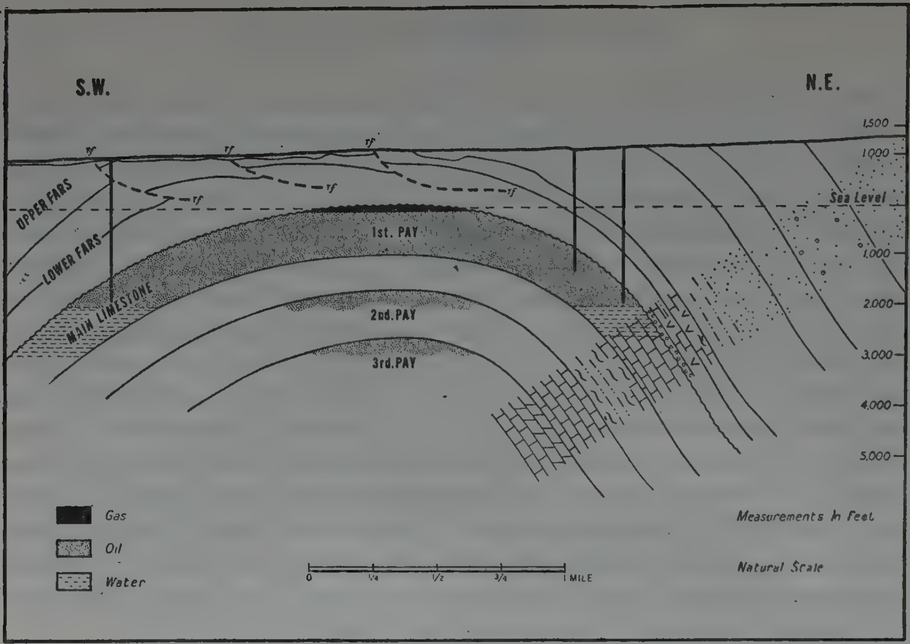

Plate VIII.—Kirkuk —typical structural cross section.

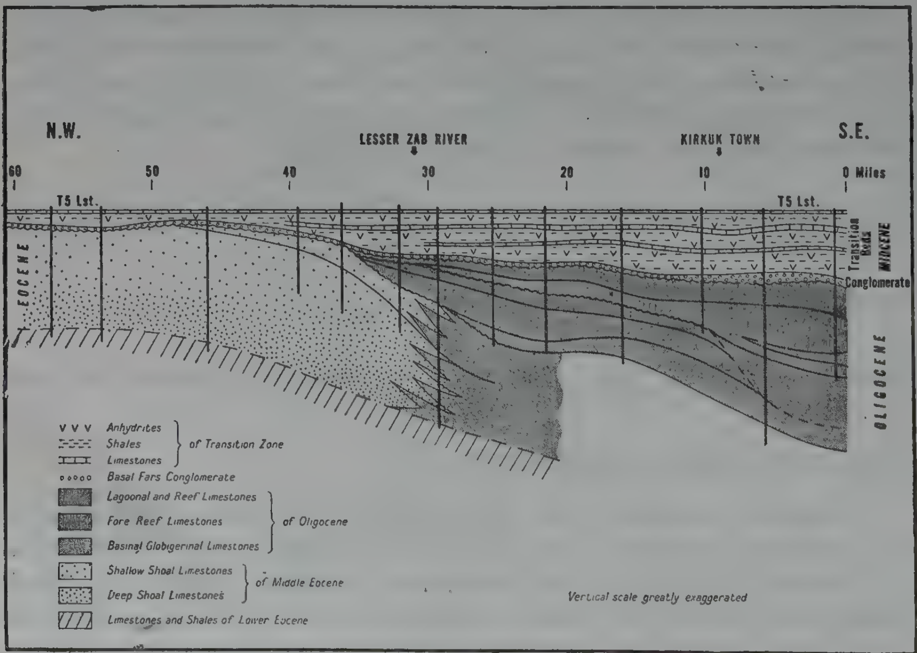

Plate IX.—Kirkuk —diagrammatic longitudinal stratigraphical section.

Eocene to Lower Miocene (Henson, 1951; van Bellen, 1956). Partial exposure of the future reservoir rock to sub-aerial erosion seems to have produced a great deal of porosity in addition to that inherent in the favourable type of sediment. Almost perfect cover is provided by Lower Fars formation of alternating clays, anhydrites and thin limestones with a thick development of rock salt: this laminated cover has been sufficiently plastic under the pressure of overburden and tectonic squeezing to seal adequately any fractures caused by folding in beds above the reservoir. Fractures did develop in the reservoir, a minority of large size including faults several kilometres long and with throws up to 180 m. (600 ft.), but consisting mainly of myriads of joints and minor breaks apparently traversing the reservoir complex in all directions (Daniel, 1954).

The cause of this intensive shattering is not known: it is becoming evident as drilling proceeds on neighbouring structures that in such degree it is a phenomenon confined to Kirkuk and is therefore presumably of some special but local tectonic origin; but it is fundamentally responsible for the immense productivity of Kirkuk wells. It is noteworthy that, despite the fracturing exhibited by the Tertiary reservoir, accumulations of oil of uncertain importance have been preserved in the Upper and Middle Cretaceous strata (Wellings, 1953).

Bai Hassan.

This structure is of comparable stratigraphic setting to Kirkuk, and oil occurs in a similar complex of reef, backreef and forereef limestones of Tertiary age, sealed in by Lower Fars formation as cover (van Bellen, 1956).

The anticline is much smaller than Kirkuk and is much less cut by fractures and joints.

The general nature is shown by the cross section (Plate X).

Jambur.

This structure is thought to lie basinwards of the Tertiary shoal and reef complex of Bai Hassan and Kirkuk, which belt probably passes considerably farther to the NE.

Oil is found in Middle to Lower Miocene marly to oolitic limestones interbedded with anhydrite and tending to pass laterally downflank

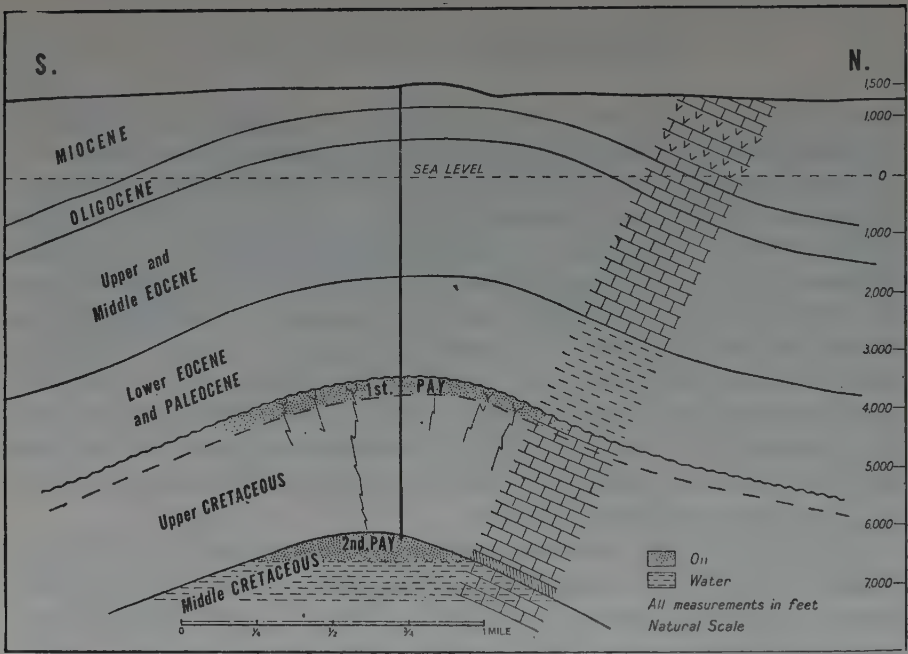

Plate X.—Bai Hassan —structural cross section.

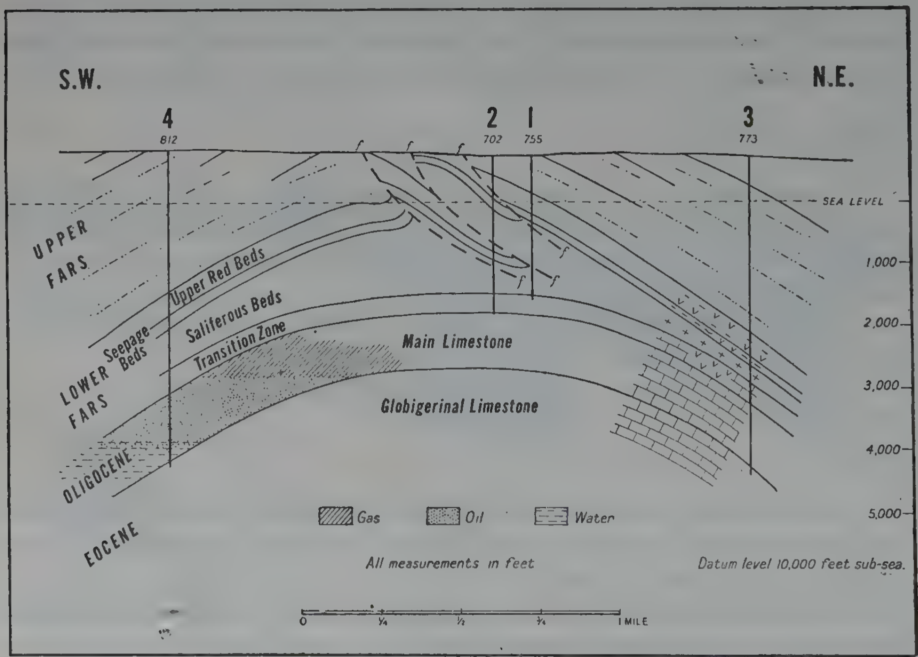

Plate XI.—Ain Zalah —structural cross section.

into anhydrite. The cover is Lower Fars. Fractures and joints exist but to a very minor extent as compared to Kirkuk: nevertheless where they are abundant they make these seemingly unpromising reservoirs capable of considerable production.

M.P.C. CONCESSION —*Ain Zalah Field.*

The structural cross section (Plate XI) illustrates conditions in this field. The First Pay (fractured marly limestone of Upper Cretaceous age) is fed from the Second Pay (Middle Cretaceous fractured and porous limestone and dolomite) through fissures traversing the intervening 600 m. (2000 ft.) of barren rock (Daniel, 1954).

Butmah Field.

This structure is very similar to Ain Zalah, and production is from a reservoir just like that of the Ain Zalah First Pay.

B.P.C. CONCESSION —*Zubair Field.*

The structural cross section (Plate XII) gives salient data. Heavy sulphurous and very viscous crude (20° API) is found in the lower limestone beds of the Lower Fars and the upper sands of the underlying Ghar formation here, and also at Nahr Umr some 24 km. (15 miles) to the north. This is the so-called "First Pay".

"Second Pay" oil (26° API) occurs in non-homogenous limestone in the uppermost part of the Middle Cretaceous in the Shu'aiba sector only of the Zubair field: the cover is some rather shaly marl and marly limestone.

The "Third Pay" oil (36° API) occurs in sands of the Zubair formation (Lower Cretaceous) under a cover of dark shales belonging to the same formation; the oil is under-saturated with gas.

The "Fourth Pay" oil (42° API) in sands of the same formation but separated from the "Third Pay" by some 67 m. (220 ft.) of black shale, is, however, fully saturated with gas.

Rumaila field.

The stratigraphy resembles that of Zubair closely down to the Lower Cretaceous. In the Zubair formation at Rumaila there is less

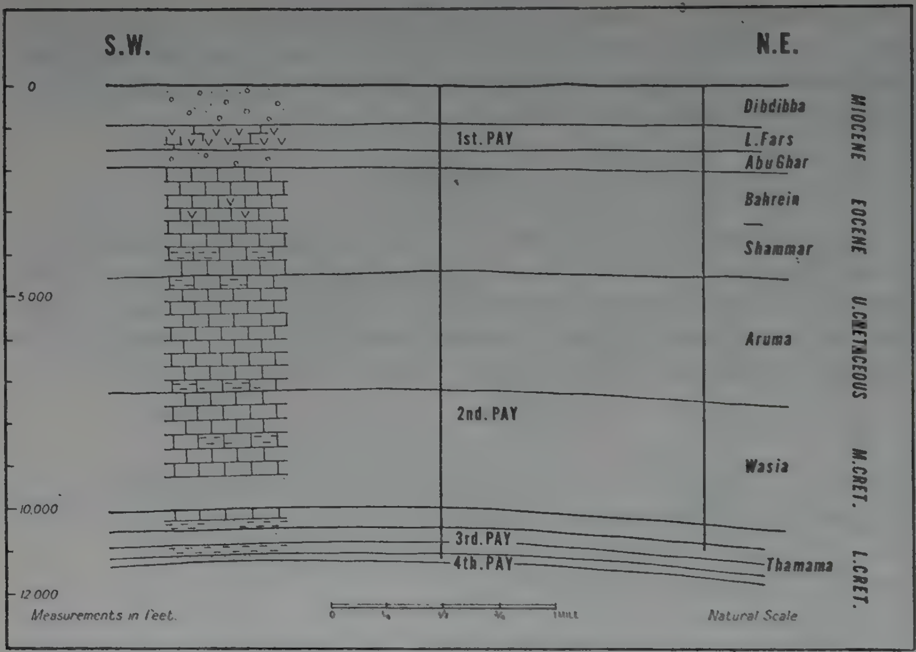

Plate XII.—Zubair —structural cross section.

shale and more sand, and the sand is generally slightly coarser and looser with consequent increased permeability. Individual sand members picked out at Zubair are not clearly separated at Rumaila where they merge into a single sand body. As a consequence there is no separate "Fourth Pay" with light oil, and there is only one oil throughout, this being of about the same gravity (36° API) as the Zubair "Third Pay" oil.

HISTORY AND METHOD OF DISCOVERY OF THE MAIN FIELDS

This is dealt with under the heading of Exploration.

DEVELOPMENT AND EXPLORATION CONDITIONS IN THE MAIN FIELDS. NORTH IRAQ PROVINCE.—I.P.C. CONCESSION

Kirkuk field.

The Tertiary reservoir rock in this field, which is some 60 miles long and two miles wide, consists, of a heavily fractured limestone

sequence having a thickness of about 1000 feet. Porosity through the section varies within wide limits, a main productive section being overlain and underlain by non-porous limestones.

The field is divided into three domes increasing in depth from 1000 fet below the surface in the southeastern dome (Baba), 2000 feet in the middle dome (Avanah), to 2500 feet in the northwestern dome (Khurmala).

Production has been confined to the Baba and Avanah domes.

Initially there was no free gas in the reservoir except in the Khurmala dome, and in the Baba and Avanah domes the oil was everywhere undersatured. With the decline in reservoir pressure consequent upon production a substantial gas-cap has now developed in the Baba dome, and the formation of a gas dome at Avanah has also started. Gas/oil ratios are 200 to 220 cu. ft. per barrel, and the gravity averages 36° API.

The producing mechanism at the present time is predominantly water-drive, but a gas-cap drive is developing as more and more gas is evolved from the crude. In this connection, it is of interest to note that with the open system of fissures, a movement of oil, due to convection or diffusion, is taking place in the reservoir towards the region of the gas-oil level, resulting in a lowering of saturation pressure and consequent release of additional gas to the dome.

Reservoir connection throughout the field is so free that pressure response between any one part of the field and another is a matter of a few hours. Moreover, the wells are capable of high rates of production with a very small bottom-hole differential pressure. Thus, for a flow-rate of 20,000 b.p.d., 35% of the existing producers have a draw-down not exceeding 5 p.s.i., 85% not exceeding 15 p.s.i. whilst in no case does the draw-down exceed 24 p.s.i. (Freeman. 1952 a & b; Daniel, 1954).

Bai Hassan Structure.

This lies about 8 km. (5 miles) southwest of the flank of the Kirkuk structure and runs parallel to it.

Exploratory drilling has proved a limestone reservoir in which there is a large gas-dome, and in which the oil is underlain by a tilted water-table.

The limestone body has a total thickness of several hundred feet and an average porosity of 20%.

The main productive section is of variable thickness with permeabilities as high as 200 m.d.

This is overlain by a section of intermittent permeability, and underlain by one in which the permeability is almost nil.

The oil is fully saturated, with a G.O.R. of about 600 cu. ft./bbl. The gravity is about 34° API.

Jambur Structure.

This lies about 40 km. (25 miles) S.S.E. of Kirkuk town, and some 16 km. (10 miles) S. W. of the extension of the Kirkuk line of strike.

Drilling to date has revealed the existence of a complex reservoir having a total thickness of several hundred feet, the entire middle section of which consists of impermeable limestones and anhydrites of variable thickness. The upper and lower pay zones of somewhat more porous and permeable limestones, are thus isolated from one another, and have different heights of oil column and independent fluid levels.

The G.O.R. of the oil which is fully saturated is about 1500 cu. ft./bbl. The gravity is about 41° API.

M.P.C. CONCESSION

Ain Zalah Field.

This field consists of two separate reservoirs, some 2000 feet apart, vertically. They are, however, connected by localised fractures and are thus subject to a single pressure system.

The upper undersaturated oil is found in fractures in the crestal portion of the structure, the matrix of the reservoir rock being saturated with salt water. These fractures die out flankwise and on the plunges, so the pool is limited in all directions. No oil/water level has been observed and, in depth, oil is restricted by the dying out of the crestal fissures.

The lower reservoir is of the conventional pore type and has a

very effective water drive which is operative to a varying degree in the upper reservoir depending on the rate of offtake therefrom.

Acidisation of the upper reservoir has been most effective and wells of high initial production rates have been obtained; though these could not be maintained except at very steep pressure declines detrimental to ultimate recovery.

Development in these circumstances has been irregular in pattern as there has been no clearly defined control either reservoir or geological, to follow.

The gas/oil ratio is about 290 cu.ft./bbl., and the gravity about 33° API.

Butmah Field.

A similar pool to the upper reservoir at Ain Zalah, with an underlying water-bearing lower reservoir which is not, in this case, connected by fissuring.

Oil is contained in fractures and good communication exists. Production to date has been by expansion of the undersaturated crude, with a resulting steep pressure decline. No associated aquifer has yet been found.

The gas/oil ratio is about 200 cu.ft./bbl., and the gravity 29° API.

BASRAH PROVINCE.—B.P.C. CONCESSION

Zubair Field.

The Third Pay reservoir section is a sandstone/shale complex, some 330 feet thick, in which four main sand members can be distinguished; averaging about 200 feet in total.

The oil is undersaturated by roughly 2000 p.s.i. and, therefore, no primary gas cap is present. Water has been encountered on both flanks at sensibly the same elevation.

The quality of the oil varies with structural position, so that crestal wells have a G.O.R. of approximately 800 cu.ft/bbl. and low flank wells one of 600 cu.ft./bbl. Oil gravities show a similar trend sugesting some gravitational segregation of oil within the reservoir. The average value is 36° API.

Porosity averages 20% and permeability 250-400 m.d. A spacing of 1 well for 866 acres has been adopted on a diamond grid, and pressure interference on a small scale has been noted.

The wells average 11,000' in depth and are completed by selective shaped charge perforation of the 5.1/2" oil string which is cemented through the producing section. Initial flowing pressures average 1600-1800 p.s.i. at 5000 b.p.d.

A feature of production has been the high salt content of wells located high in the structure. No water has been detected but the oil may contain up to 1000 lbs. of salt per 1000 bbls. It is believed that this salt is derived from water saturated siltstones associated with oil sands, and a desalting plant is being installed.

The reservoir mechanism to date has been expansion of the under-saturated oil, resulting in a steep pressure decline. A poorly effective water drive may be operative on one flank.

The Fourth Pay occurs some 220 feet below the Third Pay and consists of a thinner but similar sandstone/shale complex, containing, however, a better quality oil of average gravity 42° API. A large primary gas cap is present which may be condensate bearing. Sand characteristics are less favourable than in the Third Pay and high pressure draw-downs are associated with relatively low production rates.

Rumaila Field.

The reservoir section at Rumaila is in the same geological formation as at Zubair, but contains a much higher proportion of sand and the shale and siltstone members are noticeably absent. Porosity averages 25% and permeability 1000 m.d.

The oil is even more undersaturated than at Zubair, i.e. saturation pressure is 2500 p.s.i. below initial reservoir pressure. A horizontal oil/water level has been proved to exist throughout the reservoir.

Some variation of quality with structural position is present, but is not nearly so marked as at Zubair. The gas/oil ratio averages 700 cu.ft./bbl., and the gravity of the crude 36° API.

The field has only recently gone on production and, so far, by oil expansion. From the characteristics of the reservoir sand, a water drive may be expected.

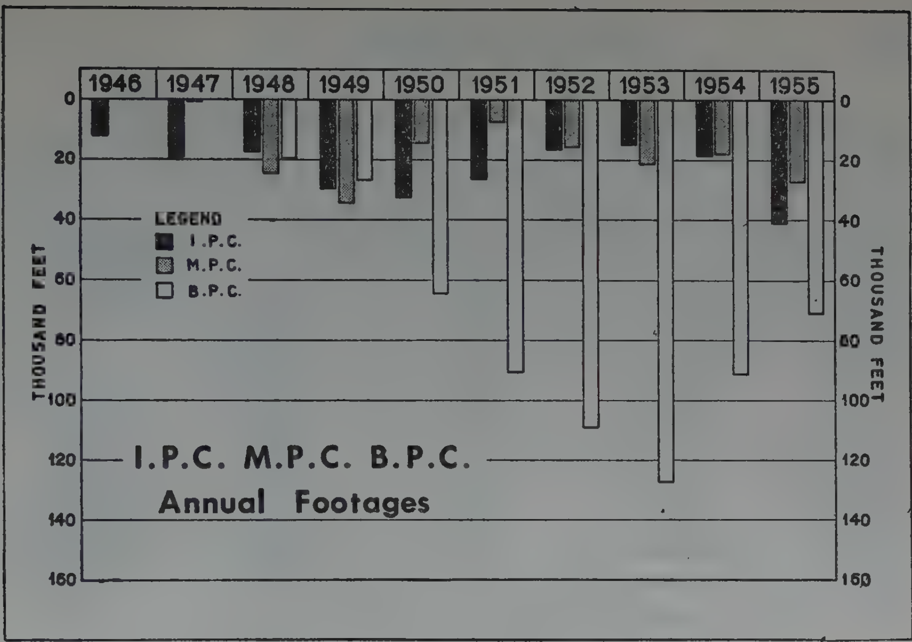

Plate XIII.—Annual drilling footages, I.P.C., M.P.C., B.P,B,

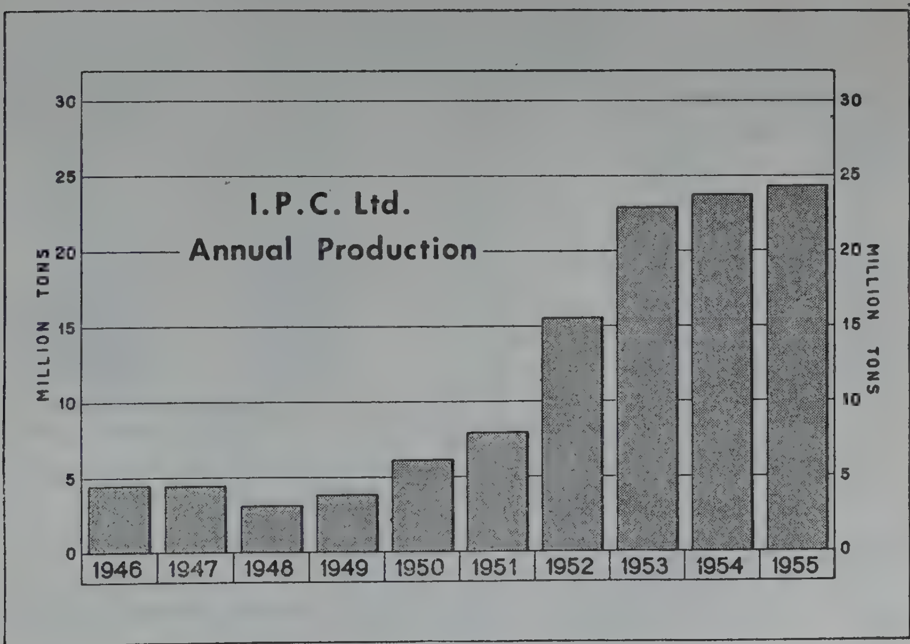

Plate XIV.—Annual oil production, I.P.C.

DRILLING AND PRODUCTION STATISTICS

DRILLING FOOTAGE

	North Iraq Province			Basrah Province
Year	I.P.C.	M.P.C.	Total	B.P.C.
1946	12,346	——	12,346	——
1947	19,142	825	19,967	——
1948	17,403	24,447	41,850	19,857
1949	29,939	34,421	64,360	26,902
1950	32,654	14,443	47,097	64,832
1951	26,119	7,236	33,355	90,833
1952	16,676	15,946	32,622	109,203
1953	14,951	21,525	36,476	127,142
1954	18,786	18,019	36,805	91,354
1955	41,012	27,288	68,300	71,063

PRODUCTION-TONS

	North Iraq Province			Basrah Province
Year	I.P.C.	M.P.C.	Total	B.P.C.
1946	4.402,828	——	4.402,828	——
1947	4.407,040	——	4.407,040	——
1948	3.102,796	4,045	3.106,841	——
1949	3.802,981	8,126	3.811,107	10,533
1950	6.160,765	5,501	6.166,266	4,010
1951	7.987,024	7,233	7.994,257	137,176
1952	15.552,715	270,765	15,823,480	2.238,177
1953	22.865,538	1.277,138	24,142,676	3.082,000
1954	23.731,108	1.283,442	25.014,550	4.600,027
1955	24.235,343	1.282,428	25.517,771	7.231,528

PETROLEUM EXPLORATION

Geological Exploration.

This falls into three stages, viz: 1926-1931; 1931-1940; and 1946-1956.

1) 1926-1931.—Stratigraphic reconnaissance in the mountains of SE Kurdistan, and in the western desert of Iraq and structure mapping of surface anticlines; all by the Turkish Petroleum Co. Ltd., which became the Iraq Petroleum Co. Ltd. in 1929 (Barber, 1948; Longrigg, 1954). During this period several of the foothills anticlines were mapped and thereafter 12 of them tested by one or more holes, many of which failed owing to difficult drilling conditions. To the credit of this geological and drilling exploration must be put the discovery of the enormous Kirkuk field and of the large but non-commercial Qaiyarah accumulation, both in 1927.

2) 1931-1940.—The I.P.C. concession, which had previously covered all Iraq, was modified in 1931 and restricted to the Mosul and Baghdad vilayets east of the Tigris River, as it still remains. A concession over the whole of Iraq lying to the west of the Tigris and north of latitude 33, was acquired in 1932 by the British Oil Development Corporation, Ltd., but reverted to the Iraq Petroleum Company group of companies in 1935.

Exploratory work by the I.P.C. during these years was concerned mainly with the development of Kirkuk oilfield.

The B.O.D., however, devoted much effort to surface geological mapping of numerous anticlines, and a great deal of drilling work to the development of Qaiyarah (which was extended to Najmah and Jawan), and to the testing of several adjacent structures one of which, Ain Zalah, being found to carry good quality oil in 1939. In 1943 the company's name was changed to Mosul Petroleum Co. Ltd.

In 1938 a concession covering all of Iraq south of the existing concessions was granted to Basrah Petroleum Co. Ltd. (Barber, Longrigg, op. cit.). Geological parties were in the field from that time on, though in very limited force during the war years. During these years all geological field work was suspended in other areas.

3) 1946-1956.—In 1946 a large scale stratigraphic survey was undertaken in the Kurdish mountains, and in the western desert wherever deep formations are exposed. The results have been extrapolated into the I.P.C. and M.P.C. oilfield areas and have been of great value in making forecasts for wildcat wells. The geological picture so built up has been continually revised from the study of samples from some 50 wells which have been drilled into the Mesozoic.

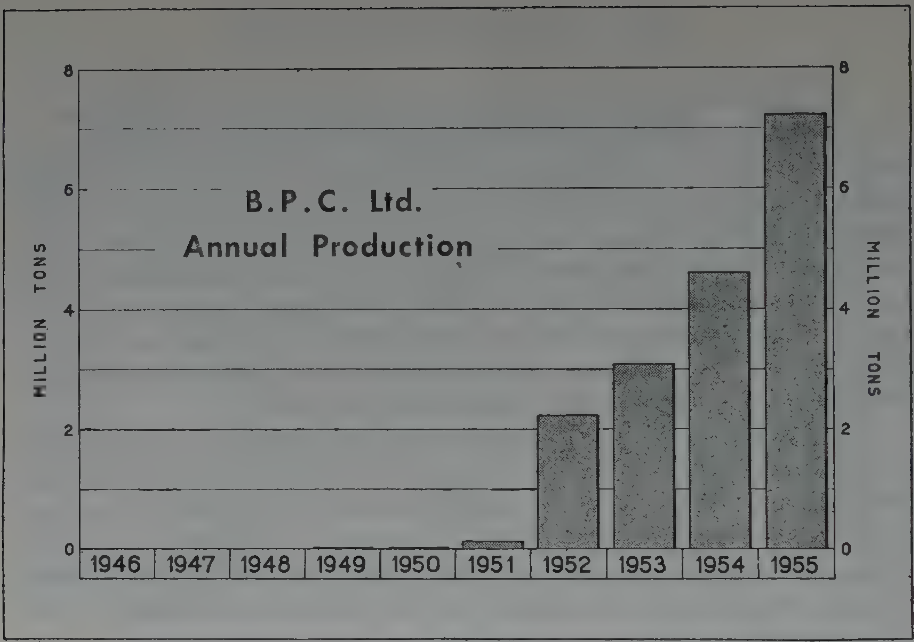

Plate XV.—Annual oil production, M.P.C.

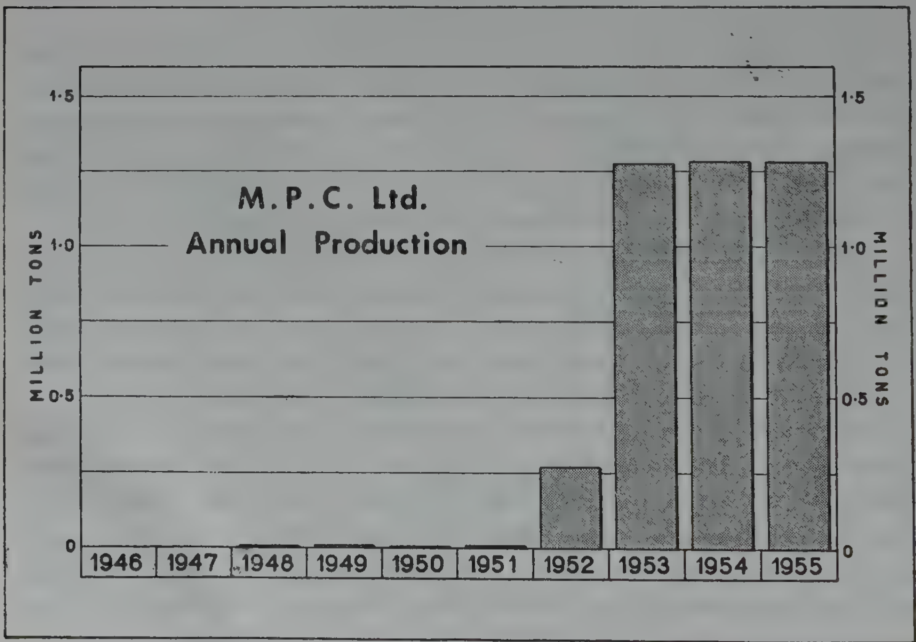

Plate XVI.—Annual oil production, B.P.C.

In addition air photo-surveys have been made covering the unmapped part of Kurdistan (12,500 sq. km. 4825 sq. miles), and of part of the western desert (4000 sq. km. 1544 sq. miles).

To the credit of this geological and drilling exploration must be put the discovery of gas at Chemchemal in 1952, and of oil at Butmah in 1952, at Bai Hassan in 1953 and at Jambur in 1954.

Geological field survey in the Basrah concession was replaced in 1945 by an extensive geophysical survey program. In 1951 geological field survey was resumed in the western desert region, and since 1954 this has been supplemented by structure drilling.

Geophysical Exploration.

Before the war some reconnaissance gravity survey was carried out in the M.P.C. concession, and to a lesser extent in the B.P.C. concession.

Geophysical survey as a major exploration method was adopted immediately after the war, gravity, magnetic and seismic parties being introduced into the concessions in 1946, since when they have been continuously at work. Practically the whole prospective area has now been covered by a reconnaissance network of gravity and magnetic stations with an average spacing of roughly one station per 4 sq. km., with more detailed work in selected areas. Suitable leads are followed by seismic detailing, which is now being fitted into a system of regional traverses. Naturally the greater part of the detailed work is in the Mesopotamian plains where surface geology cannot help the exploration, resulting in a major proportion of the effort in the B.P.C. concession. The cores of some steeper exposed structures in the M.P.C. and I.P.C. areas have, however, also been the subject of special seismic studies.

The amount of effort by crew months in each area during the period 1946-1955 is given below:

Area	Party	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	Total
IPC	Grav							8	2	4	6	20
	Seis		1								4	5
MPC	Grav		3	8	4	16	12	5				48
	Seis		1	5	7	7	10	12	12	8	13	75
BPC	Grav	10	7				27	48	43	26	12	173
	Seis	6	10	16	16			11	28	36	31	154

TOTAL Gravity 241
Seismic 234

To the above geophysical work must be credited the discovery of the large Zubair and Rumaila oilfields in 1949 and 1953 respectively, and, in confirmation of surface geology, of the small Nahr Umr structure also in 1949.

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SYMPOSIUM SOBRE YACIMIENTOS DE PETROLEO Y GAS
XX CONGRESO GEOLOGICO INTERNACIONAL

JAPAN

(JAPÓN)

OIL AND INFLAMMABLE NATURAL GAS IN JAPAN *

KATSU KANEKO
Director Geological Survey of Japan.

ABSTRACT

Although the discovery of petroleum dates back many centuries Japan has been considered to be relatively poor in petroleum resources, since the indigenous production both in the past and present do not encourage the expectation of appreciable increase by major discoveries. However, as to the natural gas resources, in spite of its short development history, the production has been steadily increased since the end of the World War II.

Geographically, the petroleum production in Japan has been contributed principally from the Sea of Japan coast area of Honshû and the northern part of Hokkaidô. Geologically, the known oil-bearing horizons are in young Tertiary formations.

The natural gas, on the other hand, has been produced throughout the country and the characteristic feature is that methane gas is dissolved in underground water-bearing beds of Pliocene and later age. The reserve is considered to be enormous so that the industry is looking for further investigation. Despite the vast quantity of the presumed reserves, the natural gas associated with coal-bearing formations has not been studied geologically, consequently the utilization of this type of gas has not been started.

GEOGRAPHIC DISTRIBUTION OF OIL AND GAS PRODUCING PROVINCE

All the oil fields in Japan, with the exception of Sagara which is located on the Pacific coast, are situated on the Sea of Japan coast of the northern half of Japan (see Plate 1).

* At present the developed inflammable natural gas in Japan, on the basis of geological and producing condition, can be divided into: a) gas associated with oil-bearing formations; b) gas associated with coal-bearing formations; c) gas belonging to neither of the two.

In this article. a) is included in oil, and b) and c) are described in the chapter of natural gas. The inflammable natural gas is composed mainly of methane and is dissolved in underground water. The accumulation of such a type of natural gas has been known, except for Japan, only in the area of the mouth of the Po River of Italy and a part of the Soviet Republic. But in Japan, it is unique that this type of accumulation has been exploited since a remote past as an important natural resource and is destined to play an important role in the domestic as well as in the industrial use of this country.

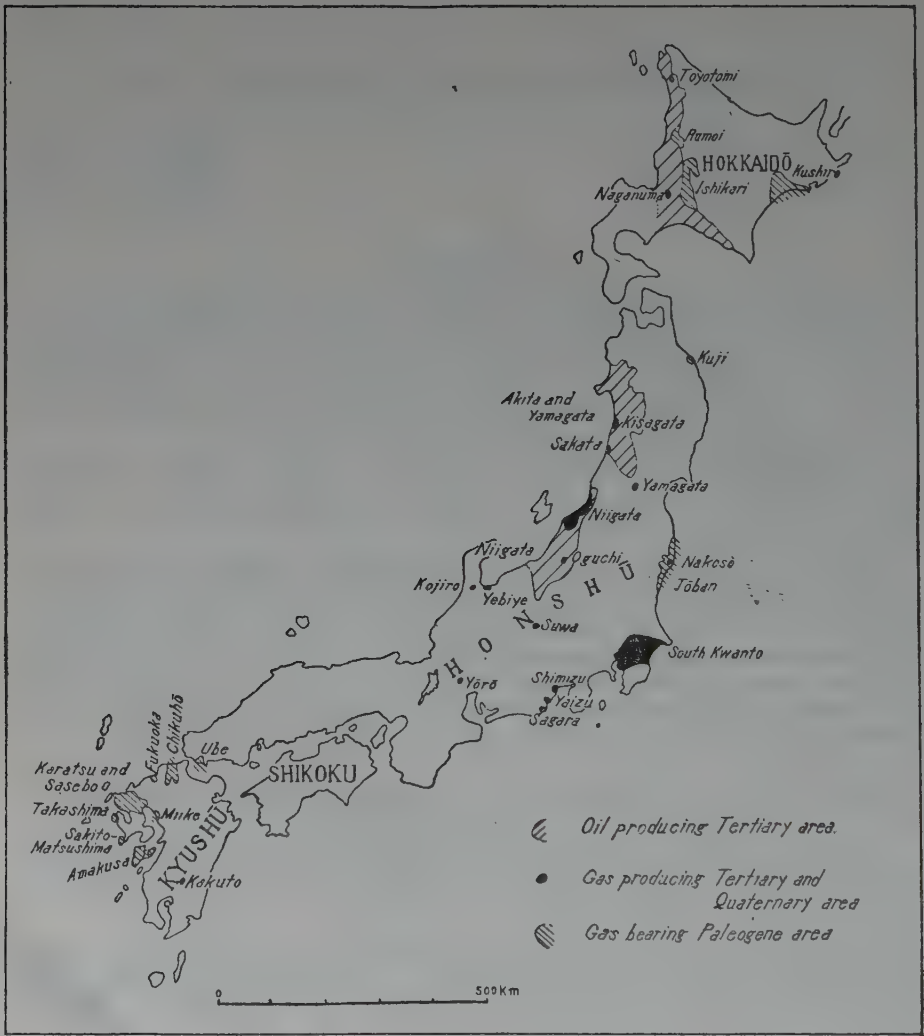

Toyotomi
Ramoi
HOKKAIDŌ
Kushiro
Ishikari
Naganuma
Kuji
Akita and
Yamagata
Kisagata
Sakata
Yamagata
Niigata
Niigata
Oguchi
Nakoso
Tōban
Kojiro
Yebiye
HONSHŪ
Suwa
South Kwanto
Yōrō
Shimizu
Yaizu
Sagara
Fukuoka
Chikuhō
Ube
Karatsu and
Sasebo
SHIKOKU
Takashima
Miike
Sakito-
Matsushima
KYUSHŪ
Amakusa
Kokuto
Oil producing Tertiary area.
Gas producing Tertiary and
Quaternary area
Gas bearing Paleogene area
0
500Km

PLATE I.

The principal oil fields are located in the hilly land on the west side of the central mountain range of Northeast Japan, or along the lowland area on the Sea of Japan coast. In detail, the petroleum-producing basins can be divided into the north, central and south of Hokkaidô, Akita-Yamagata, Niigata-Nagano and Shizuoka provinces.

As regards the gas-producing areas, except the area where the gas is associated with oil, there are two types: the one where gas is associated with the coal-bearing formations and the other where gas is dissolved in the water-bearing formations. The former is usually found in the areas where the Paleogene coal-bearing formations are developed in such regions as Hokkaidô, Honshû, and a part of Kyûshû (see Plate 1). The latter is found in the area where the Pliocene or later formations are developed. So gas fields are distributed in a scattering form, however, the most important producing-areas are found in Niigata Prefecture and in the southern part of the Kwantô plain.

GEOLOGICAL DISTRIBUTION (STRATIGRAPHY AND STRUCTURE) OF EACH OIL AND GAS PROVINCE

1. *Hokkaidô.*

The petroleum geology of Hokkaidô is shown in the geologic columnar section of each type locality in the northern part (Tempuku province), central (Ishikari province), and the southern (Atsuma province). The correlation among these provinces is shown in Table 1.

In Hokkaidô, with the exception of Hobetsu in the central province, oil is produced wholly from the Neogene-Tertiary. The Neogene-Tertiaries consisting of mud, sand, and gravel of normal marine sediments with a few pyroclastics were deposited in the sedimentary basin, in the area roughly shown by the present distribution of the formations during the Neogene time.

In the north of the Tempuku province, the formations are trending roughly NW-SE or NNE-SSW, but in the southern area, the strike of formations is controlled by the folding structure trending N-S direction, and the folding intensity is increased toward the east and is decreased toward the west.

In the Ishikari province, the direction of the folding axis is NE-SW, and the anticlinal structure is symmetrical with gentle dips in both the flanks.

CENOZOIC OF THE HOKKAIDO OIL PROVINCES

Age	Letter nom.	Tenpoku oil region	Oil & Gas Horizon	Ishikari oil region	Oil & Gas Horizon	Atsuma oil region	Oil & Gas Horizon
Quat		Numakawa f ...... sand, gravel and clay; 0–30m		Diluvium .... sand, gravel and clay		Diluvium .... sand, gravel and clay	
Pliocene	H_2	Sōrabetsu f ---- clay, sand and gravel, with "Setana" fauna; 0 — 150 m.		Zaimokuzawa f ---- sand and gravel brg. clay; 0-300 m.		Mukawa f .... conglomerate, sandstone, mudstone 850m	
Pliocene	H_1	Yuchi f .... fine sandstone; 500 – 800 m.					
Pliocene	H_1	Koitoi f .... grey mudstone with "Oiwake" fauna; 180 – 750 m. Uvig. I – Epon I – Eulim. 2 Z		Tobetsu f .... fine sandstone and grey mudstone 500 – 800 m		Moebetsu f. grey siltstone, 480 – 1,170 m Uvigerina I Z	
Miocene	G	Wakkanai f. ...... platy massive hard shale, 0 – 1300 m. Martin I – Uvig. I – Cyclam. 2 SZ	0	Morai f .... massive platy hard shale, 400 – 800 m	0	Karumai f. upper .... sandy mudst, 230-380 (Cyclam 4)	
Miocene	F_3	Masuporo form upper ...... massive mudstone, 0 – 485 m. Martin I – Haplop I SZ	0	Bannosawa f ...... glauconitic sandstone, 100—500 m.	0 0	Karumai f. middle ...... alter. sands muds 220-280 m; lower .... hard mudstone, 140-250 m. (Ammod Z)	0
Miocene		Masuporo form middle ...... Sandstone, mudstone, conglom. 0 – 1490 m. Cyclam 2 – Cyclam. 4 SZ	0	Atsuta f .... black mudstone; 350 – 800 m.		Fureoi f .... altern. sands. muds. 850-2320 m. Cyclam. 4 – Haplo-Martin. Z	0
Miocene	F_2	Masuporo form lower ...... Siltstone, lower part sandy, 0 – 1725 m. Ammod. I – Brachy I – Göes. I SZ		Hattari f altern. of sandstone and mudstone; 400 — 800 m.		Takinoue f black muds. and grey siltstone; 260 – 640 m	0
Miocene	F_2	Soya coalbrg. f Altern. of sandstone and mudstone 0 – 75 m.					
Miocene	F_1	Magaribuchi f Siltstone, 0 – 200 m. Cyclam 2 – Ostracoda Z				Momijiyama f black siltstone, 0 – 330 m. with "Poronai" fauna	0
Oligoc	E					Poronai f. black mudstone, 0 – 650 m with "Poronai" fauna	

TABLE 1

In the Atsuma province, the direction of folding axis is NNE-SSW and the folding intensity is high and, in general, the east flank of the anticline is steep but the west flank is rather gentle. Within the Paleogene and the Cretaceous formations in the peripheral area of these oil fields, many oil and gas indications are recognized but no workable oil reservoir has yet been discovered.

2. *Akita-Yamagata province.*

The type geological columnar section of the Akita district is shown in Table 2. The oil produced in the Akita-Yamagata province is wholly derived from the Neogene formations. At the base of the Neogene-Tertiary, there is a thick formation of the so-called "green tuff" which consists mainly of pyroclastics of green andesitic tuff, tuff-breccia, lava flow, agglomerate, and intrusive sheets, with some land deposits. The overlying formations consist of sandstone, mudstone, conglomerate and tuff in a normal marine sedimentary sequence. The total thickness attains several thousand meters.

It has been considered that the oil was originally formed in the Funakawa formation of the Funakawa group and the Onnagawa formation, and the reservoir rocks are considered to be of tuffaceous beds in the Funakawa and the overlying Katsurane formation. The oil accumulation in this province is controlled by an anticlinal fold whose axis runs roughly from north to south and, in general, the folding intensity is rather high. Besides, numerous faults are associated in this folding.

In some part of the Yamagata district (in the Ishinazaka and Narahashi oil fields) the oil-bearing horizon is found in the uppermost of the Neogene formations.

3. *Niigata-Nagano province.*

Table 3 shows the type columnar section of the Niigata district.

In this province, the oil is produced wholly from the Neogene formations. At the base of the Neogene-Tertiary, there lies the "green tuff", which is not very thick, and overlying beds consisting of a series of marine beds of sandstone and mudstone overlying the "green tuff". The Neogene-Tertiary is several thousand meters in thickness.

In this province, the oil is considered to have originated in the Nanatani and Teradomari formations and the principal oil-producing

CENOZOIC OF THE AKITA DISTRICT

Age	Letter Nomination		Formation name		Maximum Thickness	Main Roks	Foraminiferal zone		Remarks
Quat.	I	I_2	Katanishi f.	Terauchi f.	70 m	sand, gravel & mud	Rotalia 5 Z		
Pliocene	I	I_1	Shibikawa g.	Shibikawa f.	300+	sandstone conglomerate and mudstone; (insert. lignite)	Rotalia 3 SZ	Elphidium 4 Z	
Pliocene	H	H_2	Sasaoka g.	Tofuiwa f. / Wakimoto f.	200+	sandstone	Elphidium 4 SZ	Elphidium 4 Z	
Pliocene	H	H_2	Sasaoka g.	Sasaoka f. / Kitaura f.	700	siltstone ~ fine sandst	Uvigerina I ~ Cassidulina 6 Z		
Pliocene	H	H_1	Funakawa g.	Tentokuji f. / Katsurane f. / Kitaura f.	700	grey tuffaceous silt ~ mudstone; Alternation part with sandstone is called as the "Katsurane" or the "Kitaura"	Martinotiella I ~ Uvigerina I SZ	Cyclammina I Z	
Miocene	G		Funakawa g.	Upeer Nanakura tuff (Yabase tuff) / Funakawa f. / Lower Nanakura tuff	650	black mudstone with many tuff layers	Cyclammina I Martinotiella I SZ	Cyclammina I Z	locally upper part grey mudstone (Nomura f.)
Miocene	F	F_3	Funakawa g.	Onnagawa f. / Koya tuff	550	Hard mudstone with tuff layers	Sigmoilina 3 SZ	Cyclammina I Z	
Miocene	F	F_2	Daijima g.	Nishikurosawa f.	150	Alternation of sandstone and mudstone	Miogypsina ~ Operculina Z		
Miocene	F	F_2	Daijima g.	Daijima f.	580	tuff-breccia, sandstone & conglomerate			
Miocene	F	F_2	Daijima g.	Monzen f.		green tuff & andesite			contains the "Aniai flora"
Miocene	F	F_1	green tuff g.			green tuff & breccia			

Fossil range example: Umbonium akitanum; Turritella saishuensis; Turritella andenensis; Paleoloxodon namadicus; Comptoniphyllum–Liquidamber flora; Chlamys kanehari; Desmostylus japonicus

Igneous Rocks: liparite; dacite; basalt; andesite

Oil and gas Producing Horizon: Northern Akita belt; Kurokawa belt; Asahikawa belt; Yabase belt; Yuri belt; Innai belt; Kisagata gas field

TABLE 2.

CENOZOIC OF THE NIIGATA DISTRICT

Age	Letter Nomination		Group	Formation Name	Maximum Thickness	Main Rocks.	Foraminiferal zone.	Remarks.
QUATERN.	J			Jingamine f	150 m.	Alternation of Sand gravel and mud	(no foram.)	
QUATERN.	I	I_2	Uonuma g.	Oguni f	1300	Alternation of Sand, gravel and mud; (Insert lignite)	(no foram.)	
PLIOCENE	I	I_1	Uonuma g.	Tsukayama f.	1 100	ditto	(no foram.)	
PLIOCENE	H	H_2	Haizume g.	Wanazu f	300	massive sandstone	Rotalia 3 Z	Lateral facies change remarkable sand facies prevail in marginal part.
PLIOCENE	H	H_2	Haizume g.	Shiraiwa f	600	bluish grey siltstone	Elphidium 4 – Cibicides 3 Z	
PLIOCENE	H	H_1	Nishiyama g.	Nishiyama f.	800	dark or darkgrey siltstone and mudstone	Uvigerina 1 – Cassidulina 1 Z	Shallow facies is shown by Cassidulina 1Z
PLIOCENE	H	H_1	Nishiyama g.	Hamatsuda f	150	Alternation of sandstone and mudstone	Martinottiella – Uvigerina 1 SZ; Cyclammina 1 Uvigerina 1Z	
MIOCENE	G		Kubiki g.	Shiiya f	800	ditto	Mart-Uvig.2 SZ; Mart-Uvig 3 SZ; Cyclammina 1 Uvigerina 1Z	
MIOCENE	G		Kubiki g.	Teradomari f.	1,000	darkgrey or blak mudstone	Martinottiella 2 - Sigmoilina 3 SZ; Dorothia - Sigmoilina 3 SZ; Dorothia – Sigmoilina 3Z	Change laterally in each other
MIOCENE	F_3		Kubiki g.	Nanatani f.	1,500	darkgrey or blak hard mudstone.	Dorothia-Haplophragmoides SZ; Hopkinsina 1a –; Dorothia – Sigmoilina 3Z	
MIOCENE	F_2		Kubiki g.	Tsukawa f.	1,600	green tuff, sandstone and conglomerate	Gyroidina 1 SZ; Miogypsina-Operculina Z	
MIOCENE	F_1		Mikawa g.	(upper)	1,000	Dolerite, sandstone and conglomerate	(unknown)	
MIOCENE	F_1		Mikawa g.	(Lower)	1,000	Porphyritic Liparite	(unknown)	

Fossil Range Example | Igneous Rocks | Oil and gas Producing Horizon

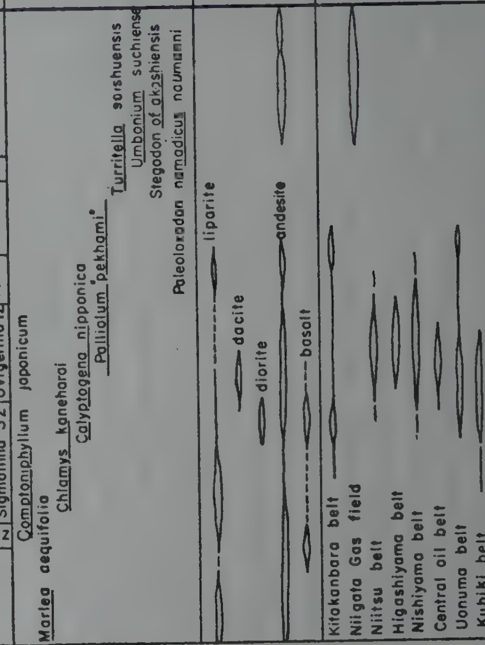


TABLE 3

formations are the immediately overlying Shiiya and Hamatsuda formations.

Most of the area covering this province is controlled by the so-called "Niigata trend", a folding structure trending NE-SW, but in the southern part (Nagano district), its trend changes roughly to N-S. The folding intensity is high and numerous faults are associated in this structural area and the oil fields are generally located within the anticlinal area.

4. *Shizuoka province.*

In this province is the only oil field situated on the Pacific coast. The productive horizon is found in the Sagara group which is considered to belong to the lower part of the Neogene-Tertiary (Miocene). The formation consists of an alternation of sandstone, mudstone and gravel beds, and the oil field is located in an anticlinal structure trending NE-SW with sharply folded flanks on both sides.

5. *Niigata district.*

The gas-producing area of the Niigata district is located at the center of the sedimentary basin of Niigata consisting of the Neogene formations. In the city of Niigata, sandstone and mudstone belonging to the Haizume group of Pliocene age are overlain by sand, gravel and mud of Pleistocene age. The alluvial and dune-sand rest directly on the Uonuma. This depositional sequence is found down to a depth of 1,000 m.

All these formations are of shallow facies and, in a broad observation, they dip slightly toward the center of the sedimentary basin (Sekiya-Uchino-Machi).

The natural gas is dissolved in the intersticial water in the formations, and the gas has been collected from gravel or coarse-grained sand beds from which a large amount of water can be pumped to the surface through the drill hole. The district which the gas can be exploited economically centers round the city of Niigata. The gas-producing basin extends 20 Km. from NE to SW with a width ranging from 4 to 6 Km., covering an area of about 1,000 $Km.^2$ The areal extension including the coastal area may cover about twice the area. The exploitation now proceeding involves the districts centering round the city of Niigata and the town of Uchino.

6. *South Kwantô province.*

The province is situated at the center of the south Kwantô sedimentary basin where the thick Neogene-Tertiaries were deposited. From the surface down to the depth of about 1,000 m., sand, gravel and mud of Pleistocene age underlain by sandstone, conglomerate, and mudstone of marine facies belonging to the Miura group (Pliocene) are found. In general, the Pleistocene formations show a shallow water facies but the Pliocene formations are represented by both shallow and somewhat abyssal deposits. Both the series are plugging gently toward the cities of Funabashi and Chiba which are situated in the central part of the basin. Thus, the Miura group in the Miura and Bôsô Peninsulas dips toward the north but its equivalent formations in the Chôshi Peninsula dip toward the west, and in the western part of Tôkyô City, the corresponding formation dips to the east.

The gas is found mainly in the water-bearing beds of the Pliocene and in places the water bears a considerable amount of iodine and bromine which give much encouragements for the economic development. The estimated workable area of the natural gas is very wide, and, if the coastal area of the Tôkyô Bay be added, its areal extension may reach to about 5,000 Km.^{2} However, at present the areas exploited for natural gas including one for iodine are limited to only a few places such as the cities of Tôkyô, Kawasaki, Chiba and Mobara.

GEOGRAPHICAL AND GEOLOGICAL DISTRIBUTION OF THE OIL AND GAS FIELDS WITHIN EACH PROVINCE

The locations of oil fields in Hokkaidô are shown in Plate 2, Akita and Yamagata in Plate 3 and 4, Niigata in Plate 5, south Kwantô in Plate 6. The stratigraphic distribution of oil and gas horizons are indicated in Table 1, Hokkaidô; Table 2, Akita; and Table 3 Niigata. In these tables, "oil belt" in most cases shows the anticlinal elongation.

STRATIGRAPHY AND STRUCTURE OF THE MORE ECONOMICALLY OR GEOLOGICALLY IMPORTANT FIELDS IN EACH PROVINCE

1. *Yabase oil field.*

During the last several years, the Yabase oil field has contributed about two-thirds of the total production in Japan and on the

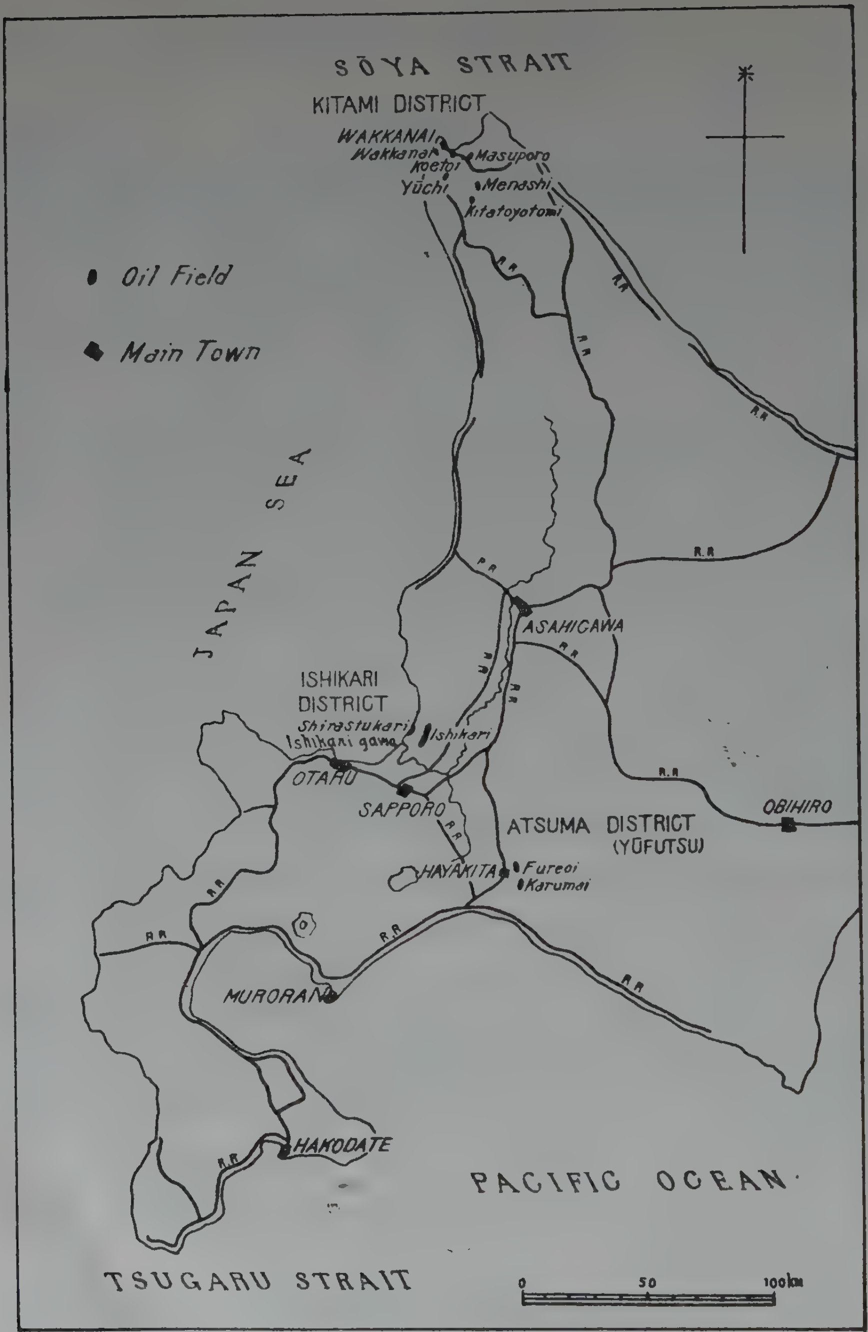
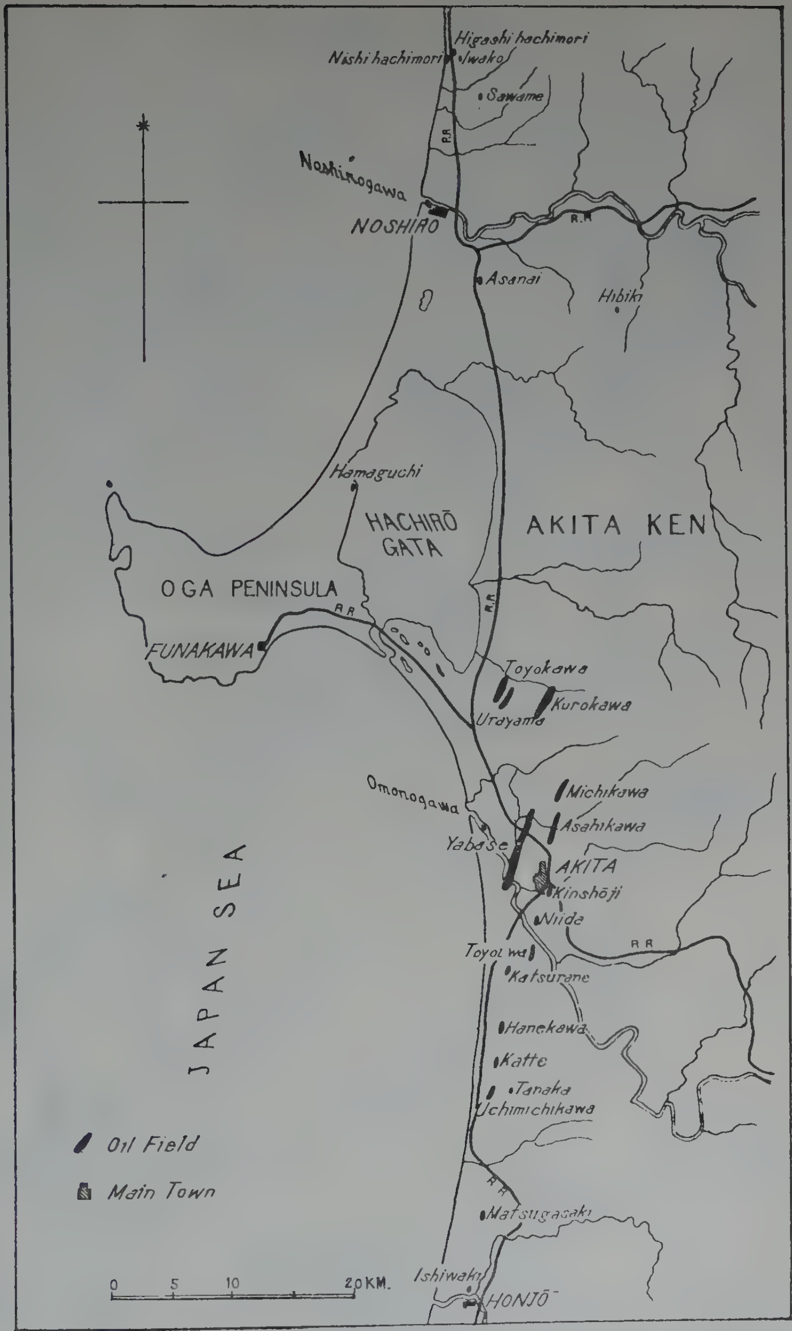
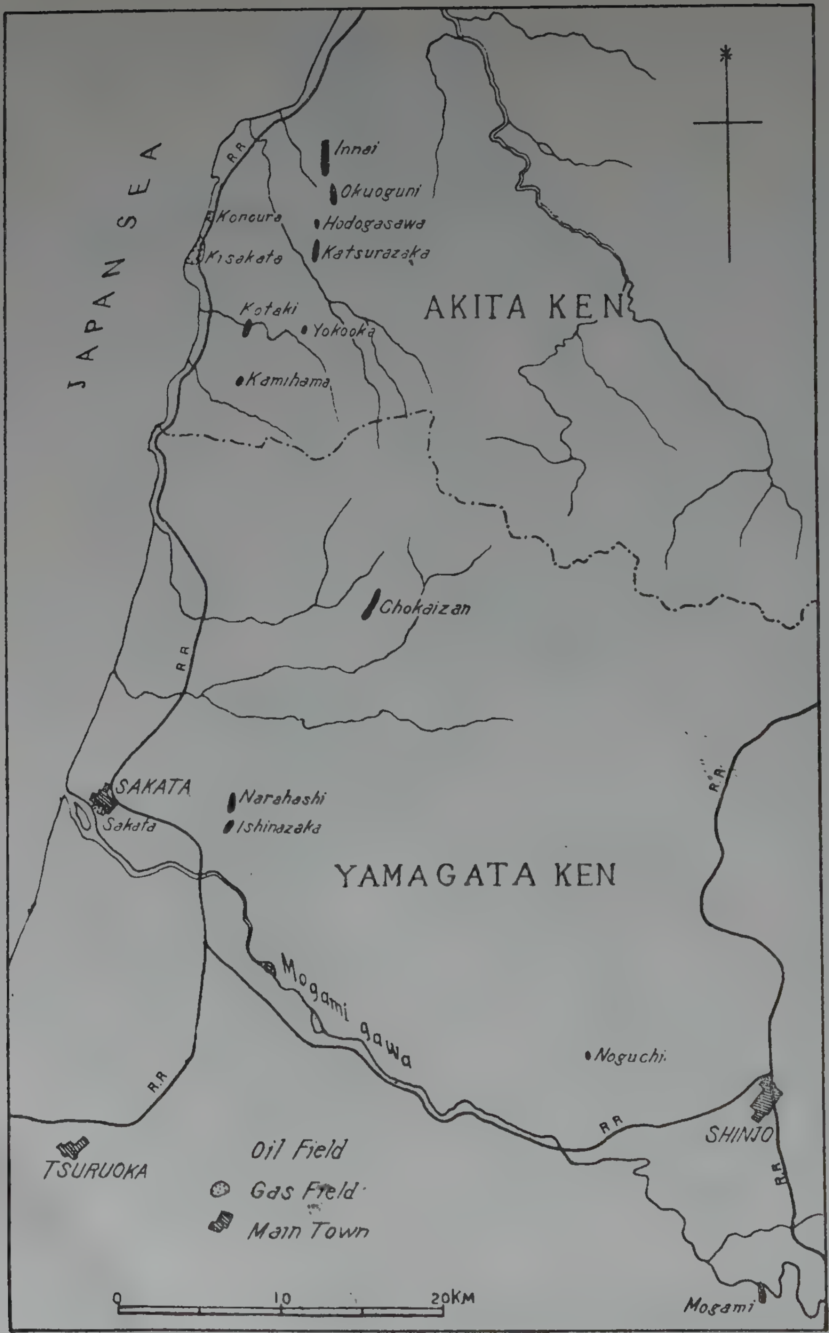

SŌYA STRAIT
KITAMI DISTRICT
WAKKANAI
Wakkanai
Koetoi
Masuporo
Yūchi
Menashi
Kitatoyotomi
Oil Field
Main Town
JAPAN SEA
R.R
ASAHICAWA
ISHIKARI
DISTRICT
Shirastukari
Ishikari gawa
Ishikari
OTARU
SAPPORO
ATSUMA DISTRICT
(YŪFUTSU)
OBIHIRO
HAYAKITA
Fureoi
Karumai
MURORAN
HAKODATE
PACIFIC OCEAN
TSUGARU STRAIT
0
50
100km

PLATE 2.



Higashi hachimori
Nishi hachimori
Iwako
Sawame
R.R.
Noshirogawa
NOSHIRO
R.R.
Asanai
Hibiki
Hamaguchi
HACHIRŌ GATA
AKITA KEN
OGA PENINSULA
R.R.
R.R.
FUNAKAWA
Toyokawa
Kurokawa
Urayama
Omonogawa
Michikawa
Asahikawa
Yabase
AKITA
Kinshōji
Niida
R.R.
Toyoiwa
Katsurane
Hanekawa
Katte
Tanaka
Uchimichikawa
JAPAN SEA
Oil Field
Main Town
R.R.
Matsugasaki
Ishiwaki
HONJŌ
0 5 10 20 KM.

PLATE 3.



JAPAN SEA
R.R.
Innai
Okuoguni
Koncura
Hodogasawa
Kisakata
Katsurazaka
AKITA KEN
Kotaki
Yokooka
Kamihama
Chokaizan
R.R.
SAKATA
Narahashi
Sakata
Ishinazaka
R.R.
YAMAGATA KEN
Mogami gawa
Noguchi
R.R.
R.R.
SHINJO
TSURUOKA
Oil Field
Gas Field
Main Town
R.R.
0
10
20KM
Mogami

PLATE 4.

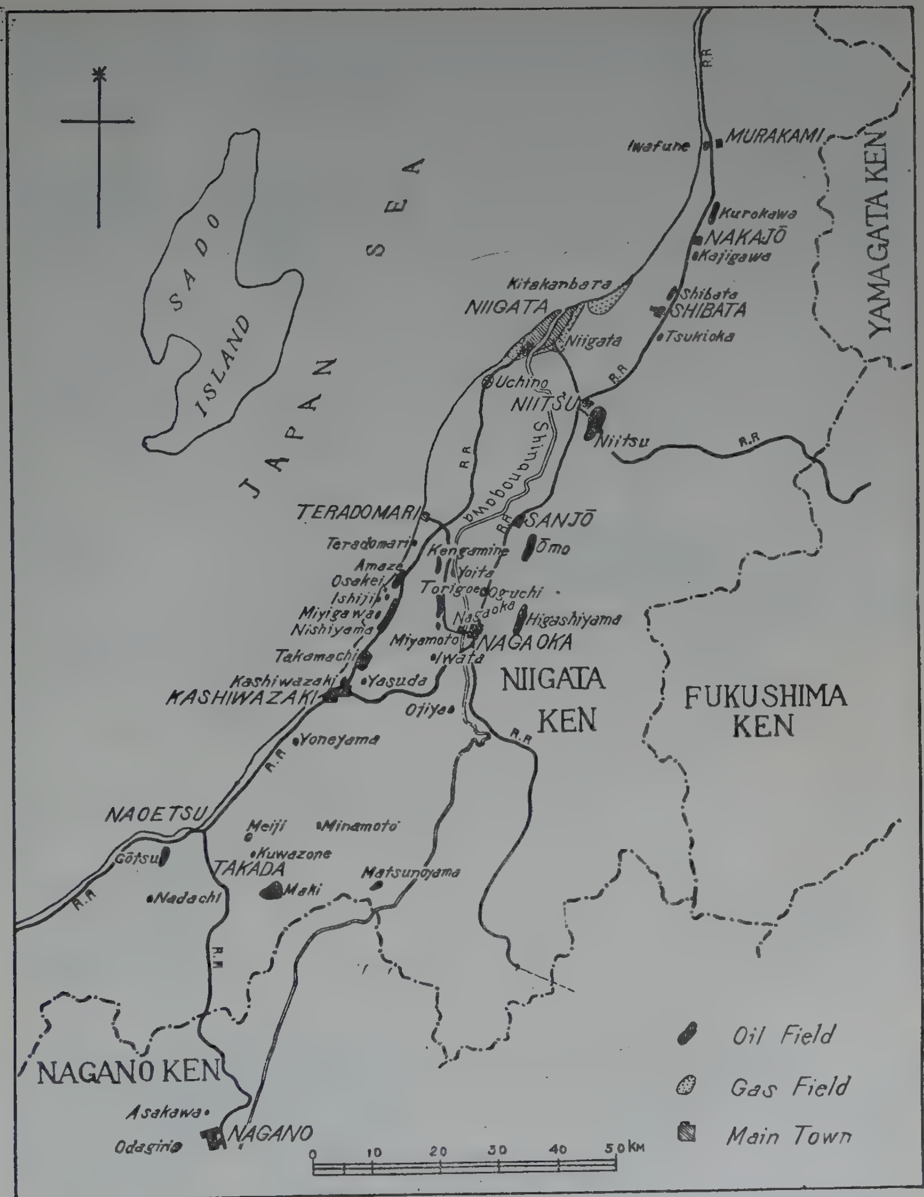

SADO ISLAND
JAPAN SEA
MURAKAMI
Iwafune
Kurokawa
NAKAJŌ
Kajigawa
Kitakanbara
NIIGATA
Niigata
Shibata
SHIBATA
Tsukioka
YAMAGATA KEN
Uchino
NIITSU
Niitsu
Shinanogawa
TERADOMARI
Teradomari
SANJŌ
Ōmo
Kengamine
Amaze
Osakei
Ishiji
Miyigawa
Nishiyama
Yoita
Torigoe
Oguchi
Nagaoka
Higashiyama
Miyamoto
NAGAOKA
Takamachi
Iwata
Kashiwazaki
Yasuda
KASHIWAZAKI
NIIGATA KEN
FUKUSHIMA KEN
Ojiya
Yoneyama
NAOETSU
Meiji
Minamoto
Gōtsu
Kuwazone
TAKADA
Maki
Matsunoyama
Nadachi
R.R.
NAGANO KEN
Asakawa
Odagiri
NAGANO
0 10 20 30 40 50 KM
Oil Field
Gas Field
Main Town

PLATE 5.

basis of the cumulative production up to the end of 1954, the field was the second largest oil producer in Japan. The field is situated at about 2 Km. west of Akita City on a structural trend extending about 9 Km. from north to south in general, and its active exploitation has been carried out since 1933.

The whole area of this field is covered by both the alluvium and Pleistocene formations. According to the drilling record (Kôya R. 34), the thickness of each formation is confirmed as follows: the Sa-

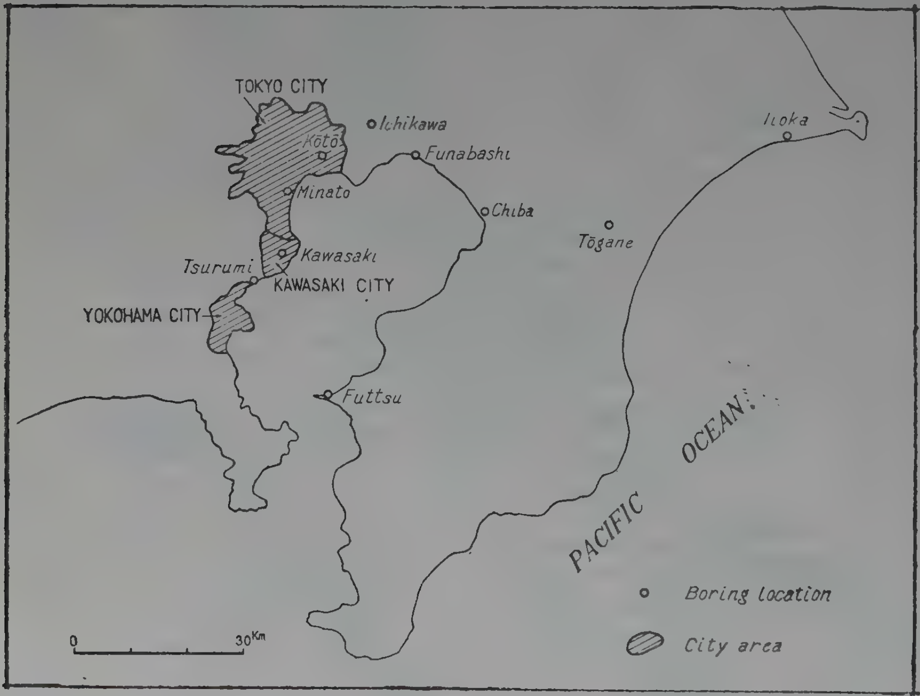


PLATE 6.

saoka formation 150 m., the Katsurane formation 200 m., and the Funakawa formation 400 to 700 m., in a downward sequence. Further toward below the 1,000 m. mark, the Onnagawa formation with a thickness of about 1,000 m. is found. The oil field is located on a narrow anticlinal structure about 10 Km. from NNE to SSW called the Yabase anticlinal fold. In general, the anticline is somewhat asymmetrical having the west flank dipping steeply (50°-60°) and the east

flank dipping gently (25°-30°). The folding is less intense on the upper horizon than the lower. The field can be separated into two districts, Kôya and Yabase, by a thrust fault which is running from NW to SE.

In the Yabase field the reservoir beds are found in the sandstone of the Katsurane formation and the tuffaceous bed in the Onnagawa formation in which a total of twelve producing zones have so far been recognized. Thus Zone I is found in the sandstone of the Sasaoka formation near the boundary of unconformity with the Pleistocene at a depth of 20-100 m.; Zone II is at the depth of 150 m. in a sandstone of the upper part of the Katsurane; Zone III is in the sandstone of the middle Katsurane at a depth of about 200 m.; Zone IV is found in the upper part of the Yabase tuff at the depth of 350 m.; Zone V is in a thin tuffaceous bed in the upper part of the Funakawa formation at a depth of about 450 m.; Zone VI is a thin tuff bed at the depth of about 800 m.; Zone VII is a thin tuff at the base of the Funakawa formation at the depth ranging from 900 to 1,000 m. The Zones VIII, IX, X, XI and XII all consist of tuff beds found in the Onnagawa formation and the depths are ranging from 1,200 to 2,500 m. However, Zones XI and XII have not been exploited.

2. *Niitsu oil field.*

The field was discovered in 1870 and on the basis of cumulative production up to the end of 1954, the Niitsu field ranks at the first place in the oil production of Japan. The surface rocks in this field consist of the Koguchi and Kanazu formations which can be correlated to the Nishiyama and Shiiya formations respectively, but in the Koguchi district, for instance, the Koguchi formation extends down to a depth of 200 m. and the Kanazu formation extends down to 600 m., from the Koguchi formation. Below the Kanazu formation, the Teradomari and Nanatani formations extend down to 1,250 m. level, and below that depth greenish tuffaceous rocks are found. The field is located in the Niitsu anticline and this anticlinal structure in the northern part trends from north to south, but in the southern part, there are two anticlines in a parallel direction of NNE-SSW each about 5 Km. in length. The oil fields are located mainly on the west flanks of these anticlines.

The east flanks of these anticlines are somewhat steep (20°—60°) but the west flanks are gentle (10°—20°). The folding intensity becomes less toward the crest of the anticline, and the oil and gas are accumulated at the crest of the anticline. The productive zones are called the "A" bed and Zones I, II, III, IV and V, and in these zones, the A bed is in the Koguchi formation, and Zones I and II are in the Kanazu formation; Zones III, IV and V are found in the Teradomari and Nanatani formations. The shape of oil pools is a combination of the stratigraphic trap and the anticlinal structure.

3. *Higashiyama oil field.*

The field ranks at the fourth place in Japan on the basis of cumulative oil production at the end of 1954. The unique feature as is shown in this field is that some quantity of the oil has been collected by the oil-mining operations.

The field was discovered in 1873 and is situated in a mountainous district 7 Km. to 8 Km. east of the city of Nagaoka, Niigata Prefecture.

Geologically, the Higashiyama formation which can be correlated with the Shiiya and Hamatsuda formations is exposed at the center of the field, and the Ushigakubi and Shiraiwa formation which correspond to both the Nishiyama and Haizume formations are exposed respectively in its peripheral area. The Higashiyama anticline, in which the oil field is located, trends roughly N-S for a distance of about 12 Km. A steep dip (50°—60°) is manifested on the west flank, whereas the east flank is rather gentle, so the anticline shows an asymmetrical shape. There are three culminations (Katsurazawa, Uraze and Hire) and oil has been produced from each culmination. The reservoir sands are denoted from the upper to the lower in the alphabetical order of the A, B, C, D, E, and F beds, of which the three beds namely A, B and C, are found in the Higashiyama formation and are the principal oil reservoir beds. The depth from the surface ranges from 150 to 300 m. The D and E beds are found in the Teradomari formation, and their depth ranges from 600 to 700 m. The F bed is found in the Nanatani formation.

The only oil-mining operation in Japan has been effectuated economically in this oil field.

The total length of the galleries extends 10,400 m. and within the galleries the bore-holes of 232 in number were made.

The monthly production by mining galleries is about 400 Kl.

4. *Nishiyama oil field.*

The field is situated at about 10-18 Km. northeast of Kashiwazaki, Niigata Prefecture. At the center of the field the Nishiyama formation is exposed and the Haizume formation and the Uonuma group are exposed in the surrounding area. According to the drilling records (R. 59), the depth down to 150 m. from the surface, the Nishiyama formation is penetrated and down to 750 m. the Shiiya formation is known to persist. At the depth below that, the Teradomari formation is encountered. The field is located in an anticlinal structure running from NNE to SSW in a distance of about 7 Km. Both the flanks dip about 30°, so that it is a symmetrical anticline. The reservoir beds consist of A, B, C, D, E, and I, II, III in descendig order. The A and B beds are found in the Shiiya formation. The depth of the A bed ranges from 150 to 250 m.; the B bed ranges from 300 to 350 m. and the C bed ranges from 700 to 750 m. All these beds are the principal oil reservoirs of the field. The I, II and III beds are found in the Teradomari formation and their depths range from 900 to 950 m. The field occupies the third place in Japan on the basis of the cumulative oil production at the end of 1954.

5. *Niigata gas field.*

At present, the Niigata field is an important gas field, because it contributes four-fifths of the total gas production in Japan. The history of the utilization of gas dates back as early as the pre-Meiji era.

Geologically, the surface rocks of this gas field consist wholly of the Quaternary formation. According to the drilling records, the existance of both the Uonuma group and the Haizume formation was confirmed. These formations dip very gently towards the northwest in the city of Niigata but on the south of the city, the formations lay almost horizontally. The natural gas has been collected from the water-bearing beds of the sand and gravel in the Uonuma group but the main productive horizons are the so-called G_4, S_{45}, and G_5 beds. These beds are usually encountered at a depth less than 700 m.

The degree of saturation of the gas in the underground water, or, accordingly, the rate of production, is not always controlled by the stratigraphic positions, but it is considered that the gas was originally generated at the time of deposition in the sedimentary basin.

However, the favorable conditions were followed continuously in the parts of the formation where the suitable environmental conditions for subsequent gas generation has been prevailed against the destructive process such as the invasions of surface water or the gas dispersion.

6. *Mobara gas field.*

The field is situated in the east of Mobara City, Chiba Prefecture. The history of the gas utilization is dated back to the later part of the Meiji era.

In this field the upper part of the Miura group of the Pliocene series is exposed and in its lower part, the gas dissolved in the underground water is found usually at a depth ranging from 400 to 600 m. from the surface and the gas has been collected by the drilled well.

The main producing formation is known locally as the Umegase formation. The district is shattered into numerous land blocks by a series of faults and the gas-bearing underground water pools with high gas and water ratio are formed locally by fault traps.

7. *Tôkyô gas field.*

The field occupies the southeastern part (Kôtô ward) of Tôkyô City. The surface of the field is wholly covered by alluvial deposits. According to the drilled well records (Kôtô R. I), the alluvial deposits consisting mainly of sand and mud extend down to a depth of 40 m., and down to 178 m. the rocks are Pleistocene in age and consist mainly of sand, gravel and mud. Below the 178 m. mark, the penetrated formation is the Miura group consisting of sandstone, sandy mudstone and mudstone, and the whole series dips gently towards the east. The dissolved gas-bearing water is collected from the part which consists of coarse sandstone or fine conglomerate bed belonging to the Miura group. The degree of saturation of gas in water in this field, as mentioned before, is not controlled by the stratigraphic positions of the gas-bearing formation, but it is rather atributable to the paleogeographic environment under which the beds were deposited. And this

favorable conditions might have prevailed subsequently for further generation of gas. Consequently, rich gas-bearing beds are found in the area where the formations were free from the influence of destructive process. Under such a circumstance, the exploitation and development works ought not be carried out wholly on the basis of the stratigraphical data.

HISTORY AND METHOD OF DISCOVERY OF THE MAIN FIELDS

1. *Yabase oil field.*

The Kusózu River traverses the oil field and many oil and gas indications have been found since a remote time. The seeped oil found along this river had been utilized as early as in 1868, however, a serious consideration was focussed on these indications and the first application of modern exploitation method was made in the drilling of Cable No. 1 in 1910 by the Nippon Petroleum Company. Unfortunately, however, the well failed to produce oil.

In 1933 the Nippon Mining Company completed Kazusa No. 1 in which oil was produced 0.55 kl. at a depth of only 15.50 m. and the active exploitation works were started soon after the production of 2 kl. at the depth of 59 m. was realized.

Since 1937 the drilling depth has been much augmented, thus, the oil zones such as Zones II, III, IV and V were discovered and since the year 1941, Zones VI, VII, VIII and IX were discovered by further deepening in drilling and the golden age of the Yabase field has been continued. At present a test well of 3,000 m. in depth was perforated. It is encouraging to mention that in this oil field, a part of the oil production is gained by the water-flooding and gas-injection methods, and the critical examination has been made on the next location for the application of these secondary recovery methods.

2. *Niitsu oil field.*

The utilization history of seeped oil within this field is the oldest in Japan; it dates back about 300 years ago. Since 1870 the oil was collected by the hand-dug well method to a depth of 100-300 m. The first cable-tool drilling was started in 1899 in the Koguchi district and in 1913 the first rotary drilling machine was introduced and the

oil production from deeper zones was assured. Since then the production has continuously been increased and a prosperous age of Niitsu has been realized.

3. *Higashiyama oil field.*

In the Hire district the oil from the seepages was collected since the pre-Meiji era and in 1876 there were six drilled wells. In 1888 the Hokuetsu Oil Company was established and since a successful operation was performed by the hand-dug well method its development works have been rapidly advanced. However, the most prosperous era was started after the introduction of both the cable and rotary drilling methods in 1902-1912. The oil mining operation has been practiced since 1939.

4. *Nishiyama oil field.*

The historical records of the discovery of oil seepages is dated back to 1230 and the oil is collected by the hand-dug well method which started in the first year of the Meiji era.

In 1890 a successful drilling by the cable-tool was made and the most prosperous era as an oil field was commenced soon after the introduction of the rotary drilling machine in 1913.

5. *Niigata gas field.*

A domestic utilization of gas from the artesian wells in shallow beds was started from the beginning of the Meiji era. The well was originally purported to use the water for the farm land irrigation, but in 1926 the Nippon Oil Company drilled a well in the company's backyard for the industrial purpose to a depth of 324 meters in which a deep gas zone was found. The gas was used for fuel but the proper industrial gas usage was made by the Hokuetsu Paper, Nitto Cotton-Spinning, Nippon Light Metal and Nippon Mining Companies, through the drillings to the depth of 265, 218, 151 and 1,100 m. respectively. It was reported that the amount of production of each well per day had attained more than 1,500 m^3.

The following are the number of the productive gas wells completed since 1945:

Year	1945	'46	'47	'48	'49	'50	'51	'52	'53	'54
Number of productive wells	7	13	17	30	33	26	23	24	45	43

6. *South Kwantô gas producing province.*

It was in the beginning of the Taishô era (1912), that the domestic use of natural gas from a shallow depth near the cities of Otaki and Mobara, Chiba Prefecture, was practiced. However, it was after 1926 that the gas field development by the modern drilling methods was inaugurated.

The geological and geochemical study has been carried out by the Geological Survey of Japan, and the existence of the prolific gas-bearing zones in depth was predicted. The proved districts through the test boreholes were assured in the following areas: Kôtô ward, Tôkyô (1951); Kawasaki City (1951); Futtsu (1951); Funabashi (1952); Chiba City (1952); Iioka-Machi (1954); Tôgane-Machi (1955); and Ichikawa City (1955). Among them the gas from Tôkyô, Kawasaki City, and Chiba City has been used for the industrial fuel but the gas from the city of Funabashi and Futtsu-Machi is now being used in the welfare establishments.

DEVELOPMENT AND EXPLORATION STATUS IN THE MAIN FIELDS

Table 4 shows the number of test wells sunken, wells drilled and the producing wells during the last 10 years in Yabase, Niitsu, Higashiyama and Nishiyama.

The drilled depths of these wells are shown in meters. The records on the gas of Japan can not be termed as complete but the status of boring for gas collection in the Niigata gas field and the status of the Kwantô district are as follow:

Number of the productive wells in the Niigata gas field:

(casing with 6″ diam. or more)

1948	1949	1950	1951	1952	1953	1954
19	20	26	23	26	45	43

TABLE 4.

		1945	1946	1947	1948	1949	1950	1951	1952	1953	1954
Yabase	Exploration Well	4	2	5	5	5	4	7	5	9	7
	Producing Well	20	8	6	8	12	21	35	29	26	28
	Service Well							2	6*	17	9
	Total Depth	M 12,080.80	9,376.53	8,305.25	7,554.15	23,286.80	38,311.67	55,928.80	54,737.40	59,918.10	55,848.28
Niitsu	Exploration Well		1	1					1		3
	Producing Well										
	Service Well									1	3
	Total Depth	M 1,866.40	743.70						2,695.00	2,100.80	1,976.80
Higashiyama	Exploration Well										1
	Producing Well										
	Service Well									2	8
	Total Depth	M								744.50	4,439.72
Nishiyama	Exploration Well		1	2		3	2	1			
	Producing Well	3		1		2	4	1			
	Service Well									3	11
	Total Depth	M 4,522.50	3,105.00	1,840.00	1,523.30	5,644.20	10,867.00	1,701.00		1,511.40	4,887.55

* Including 1 gas injection well.

Productive test wells completed by year in the Kwantô province:

1951.—Kôtô ward, Tôkyô City.
Kawasaki City, Kanagawa Prefecture.
Futtsu-Machi, Chiba Prefecture.
1952.—Funabashi City, Chiba Prefecture.
Chiba City, Chiba Prefecture.
1953.—Minato ward, Tôkyô City.
Yokohama City, Kanagawa Prefecture.
1954.—Iioka-Machi, Chiba Prefecture.
1955.—Ichikawa City, Chiba Prefecture.
Tôgane-Machi, Chiba Prefecture.

EXPLORATION, DEVELOPMENT DRILLING, AND PRODUCTION STATISTICS BY DISTRICT OR BY COUNTRY DURING THE LAST TEN YEARS

a) *Oil*

Number of drilled wells, productive wells and the total meters drilled by year are shown in Table 5.

b) *Natural gas*
(Records are not correct.)

c) *Oil and gas productions are shown in Table 6.*

OIL AND GAS EXPLORATION VOLUME BY PROVINCE OR COUNTRY

The Petroleum Resources Development Promotion Council, acting in an advisory capacity for the Minister of International Trade and Industry, established in 1954 the five year oil development plan in Japan.

The plan involves 151 districts for surface survey; 91 for seismic survey, 31 for gravity survey, 20 districts for structural test boring, 154 test borings and 15 districts for a secondary recovery method to be applied for the undeveloped areas of the eastern half of Hokkaidô, the Kwantô plain, Toyama district, Ishikawa, and Miyazaki, together with the present main productive districts including those of the western half of Hokkaidô, Akita district, Yamagata, Niigata, Nagano and Shizuoka. The expectation is focussed to have an annual domestic production of 1,000,000 kl. at the end of the five year plan. In order to effectuate the plan, a special company called Japanese Petroleum Exploration Company was organized in December 1955. The company

TABLE 5.

	Exploration Wells				Producing Wells		Service Wells		Grand Total	
	Test Well		Extension Outpost							
	No. of Wells	Total Depth	No. of Wells	Total Depth	No. of Wells	Total Depth	No. of Wells	Total Depth	No. of Wells	Total Depth
1945	13				78				91	51,160.43
1946	16	11,943.30	1	9,475.95	35	17,779.60			52	39,198.85
1947	6	7,822.95	13	11,961.36	25	12,075.39			44	31,859.70
1948	6	5,482.25	13	8,894.99	25	10,196.00			44	24,573.24
1949	7	6,376.15	20	19,794.12	40	30,427.74			67	56,598.01
1950	15	17,182.74	15	20,536.50	43	43.137.17			73	80,856.41
1951	24	27,520.07	21	17,072.70	61	61,668.67	2	1,550.00	108	107,811.44
1952	15	19,178.56	8	15,598.90	51	50,553.80	6	2,506.80	80	87,838.06
1953	15	24,770.45	12	19,548.95	51	52,202.15	29	11,090.30	107	107,611.85
1954	22	24,810.17	16	23,339.80	72	68,767.48	34	11,743.87	144	128,661.32

TABLE 6.

OIL AND GAS PRODUCTION

(Oil ...... Kl, gas ...... m^3) (by Teikoku Oil Co.)

	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954
Oil										
Total	239,018.23	210,244.57	200,578.54	176,344.97	215,869.54	325,539.41	366,731.98	333,843.66	329,173.84	332,798.67
Yabase	89,305.80	72,932.01	74,649.00	59,744.86	73,006.85	167,336.46	216,158.95	195,132.36	200,811.94	201,015.65
Niitsu	20,455.22	20,302.21	18,150.98	16,926.41	21,914.69	24,347.71	24,577.71	24,677.81	23,562.07	23,882.61
Higashiyama	11,316.87	10,433.40	10,444.85	10,746.79	11,258.54	11,446.12	11,338.67	10,931.65	10,644.06	10,618.34
Nishiyama	12,156.11	9,588.22	9,089.26	8,802.86	10,223.80	14,629.65	14,502.25	12,169.29	10,797.73	10,585.67
Gas (wet)	40.930.322	35.895.501	35.132.000	51.114.000	22.733.081	23.813.462	23.929.783	23.168.253	22.362.831	27.064.038
Gas (dry)					35.110.005	45.015.989	58.891.542	67.922.275	88.118.863	113.920.703
Niigata pref.				*30.999.000	26.196.000	32.401.828	42.485.950	53.889.321	66.938.350	85.669.018
Chiba pref.				5.396.000.	5.707.459	8.377.468	11.316.393	8.194.474	12.983.754	18.070.600
Tokyo pref.							426.974	1.919.053	2.424.148	2.596.170
Shizuoka pref.				556.000	1.017.307	1.527.731	1.059.805	643.662	1.084.408	1.201.964

(*.....include wet gas)

is chartered in a joint investment scheme in which a part of the investment is made by the Government; a part by private concerns and active work is commenced immediately.

As to natural gas a sum of ¥20,000,000 subsidey was offerred for its exploration by the Government in 1955 and the same amount is expected to have during the fiscal year 1956. In spite of the popularity for the gas development, no exploratory plan has been made through the Government at present.

OIL AND NATURAL GAS RESERVES

Table 7 shows the proved reserve in the whole Japan including the Yabase, Higashiyama, Nishiyama and Niitsu oil fields.

As to the estimation of workable reserves of the gas dissolved in the underground water, the confirmable criteria are not established but tentatively, the reserve status can be made in the following formula thus:

(Gas-bearing area) X (effective thickness of formation) X (porosity coefficient) X (gas and water ratio)

This is the theoritical saturation reserve, and if it is granted to apply the formula to the Niigata and Kwantô gas provinces, the reserve will attain about 70,000,000,000 cubic meters for the former and several thousand million cubic meters for the latter. It is probable that in Japan as a whole the reserve may reach as much as 110,000,000,000 m^3.

TABLE 7.

Proved Reserves

(as of the end of March, 1954. by Teikoku Oil Co.)

Japan total	3,287,600^{kl}
Yabase	1,861,900
Niitsu	415,800
Higashiyama	213,500
Nishiyama	82,800

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OIL OCCURRENCES IN KUWAIT

By A. F. Fox *

ABSTRACT

The geography of Kuwait is described and illustrated by a map, and an account given of the history of the operations of the Kuwait Oil Company in discovering and developing the oil deposits of the State.

A short description of the stratigraphy of the southeastern part of the State is followed by an outline of the structural development of the Burgan, Magwa and Ahmadi fields. A description of the structure of the Burgan, Magwa and Ahmadi fields as at present known is given, accompanied by illustrative maps and cross sections.

Recent discoveries in North-east Kuwait are mentioned, and stratigraphic variations from the facies encountered at Burgan are described. The phenomenon of gravity differentiation with depth within the Kuwait reservoirs is mentioned and a mechanism which may account for it is given. A statistical summary and a graphical representation of exploration and drilling activities and of oil production is included.

INTRODUCTION

Kuwait is an independent Shaikhdom of about 6,000 square miles in extent, situated at the head of the Persian Gulf and on its western shore. The country is bordered on the north and west by Iraq and on the south by Saudi Arabia and a Neutral Zone, over which control is shared between the Ruler of Kuwait and the King of Saudi Arabia. Its position is shown on the map, *Figure 1.*

The greater part of Kuwait is a relatively featureless, slightly undulating sandy or gravelly desert, rising gently from the sea shore in the east to a height of about 900 feet above sea level in the south west corner. Important oil seepages occur at Bahra, North of Kuwait Bay, and at Burgan.

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Figure 1. A map showing the position of the Kuwait Oilfields in relation to the surrounding countries and adjacent oilfields.

Although the landscape, especially in the eastern half of the country, appears at first glance to be featureless there is a definite coincidence of topographic incident with recent geological structure. This coincidence has proved to be of considerable value in planning exploration. Detailed aerial photographic mapping has proved a valuable aid to identifying surface structures in places where ground surveys would have been both costly and laborious.

Up to the end of the Middle Eocene era, Kuwait formed part of the Zagros or Tethys geosynclinal sea of subsidence. [1] * The character of the sediments from the Trias onwards indicate that Kuwait lay on the fringe of this sea, and was probably very close to the shore line at times. Fluctuations in the level of the sea bed were sufficient drastically to affect the character of the sediments and the rate of deposition.

Kuwait lies in the Arabian foreland [2] and, although it appears that the oil bearing structures probably owe more to uplift than to folding due to tectonic stresses, there is no doubt that the Zagros orogenic played a decisive part in deciding the present geological structure of the area.

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Particularly, thanks are due to Mr. R. M. S. Owen, until recently Chief Geologist of the Kuwait Oil Company, for the work on which the stratigraphic section of this paper is based, to Mr. V. N. Sovinsky of the Gulf Oil Corporation, for his detailed analyses of the structural history of Burgan, the results of which the writer has incorporated, and to Mr. P. T. Cox, Exploration Manager of the British Petroleum Company, for an account of the work leading to the discovery of the Burgan field in which he was associated with Mr. R. O. Rhoades, now Vice President of the Gulf Oil Corporation.

* Numbers refer to bibliography.

HISTORY OF DEVELOPMENT IN KUWAIT

A Concession was granted by the late Ruler Shaikh Sir Ahmad al-Jabir as-Sabah, in 1934 to the Kuwait Oil Company Limited. The capital of this Company is held in equal shares by the British Petroleum Company Limited, through its subsidiary D'Arcy Kuwait Company Limited, and by Gulf Oil Corporation of Pittsburgh, U.S.A., through its subsidiary Gulf Kuwait Company.

Surface geological exploration, which had taken place before the Concession was granted, had discovered the existence of three oil or gas seepages in positions which suggested they might be crest maxima on a large Tertiary uplift. The first of these at Bahra, where a surface anticline was also located, was tested by a well drilled in 1936 and 1937 to a depth of 7950 feet without encountering commercial quantities of oil or gas.

While this well was drilling gravity and magnetic surveys were made of the Concession area and a reflection seismograph survey was made over the second supposed structure at Burgan where an extensive bitumen lake had been discovered by pitting and shallow drilling in 1932. This survey confirmed the geological opinion and a well, Burgan No. 1, was started in October 1937 and penetrated the present productive series at 3672 feet in February, 1938. This well was not completed as a producer until 1953, because of mechanical difficulties which could not be remedied in the early days of development.

Between February 1938 and 1942 eight additional wells were drilled on the Burgan structure and one exploratory well was started at Madaniyat, a few miles west of what is now the Magwa field, on the third seepage originally selected.

At this stage in 1942, operations in Kuwait had to be suspended because of the international situation, the eight completed wells were plugged with cement and the one at Madaniyat had to be abandoned at 2580 feet.

Operations were resumed in 1945 and in 1946, the wells at Burgan were reopened and placed on production, and development of the Burgan field restarted. The years from 1945 to 1948 were occupied in creating the necessary base for operations and with rapid development drilling. By 1948, however, the pressure had eased a little and a new seismograph reflection party began operations. As a result of

the structural interpretation obtained from the reflection records, an exploratory well, Magwa No. 1, was spudded-in on a suspected subsidiary structure north of the main Burgan field on 28th August, 1951. This well penetrated the Wara Formation at 3943 feet and proved the existence of a substantial extension to the Burgan field.

Development drilling was then divided between the main Burgan field and its subsidiary structure at Magwa, and in the course of drilling it became apparent that the structure of the Dammam Limestone which is an easily identifiable and correlatable horizon throughout the area, reflected fairly accurately the structure of the producing beds. Because of this coincidence, a programme of structural drilling was carried out during 1951 and 1952 in order to discover the structure of the Dammam Limestone on the prominent surface feature known as the Ahmadi Ridge, over which it had proved impossible to obtain satisfactory energy returns from reflection shots. This is a long ridge running approximately north to south and lying to the north-east of the Burgan and east of the Magwa fields. The structural drilling programme was carried out between October, 1951 and May, 1952, and involved a total of 13,419 feet of drilling in forty-five holes. It showed that there were several subsidiary highs along the axis of the Ahmadi Ridge and a location was selected on one of them.

Ahmadi No. 1 started drilling on 20th August, 1952, and was completed as a producer in the Wara Sand and the Mauddud Limestone in December of that year. The well proved to be much lower on the Cenomanian beds than had been expected from its position on the Dammam Limestone, and it was concluded that the Ahmadi Ridge structure was of later formation than either the Burgan or Magwa fields, since little erosion of the Wasia beds had taken place during the Aruma-Wasia unconformity.

In the course of structural drilling, other highs had been noted to the north of Ahmadi No. 1, and wells Ahmadi Nos. 2 and 3, were drilled on them.

These wells proved that opposite the Magwa field the Post Middle Eocene elevation along the Ahmadi Ridge had been sufficient to raise the Third and Fourth Sands of the Burgan Formation high enough to allow oil to be produced from them.

After the drilling of these two Ahmadi wells, the general outline of the Burgan/Magwa/Ahmadi field became known and subsequent

drilling only served to extend knowledge towards the flanks, and to enable more accurate and detailed pictures of the central portion to be drawn.

Subsequently, attention was directed to a surface structure at Umm Gudair about thirteen miles to the west of the Burgan field. Reflection seismograph and structure drilling confirmed the presence of a closed structure coincident with the surface rise. A wildcat well was therefore spudded-in on 14th February, 1954. This well found the top of the Wara Formation at 5333 feet and showed that the thickening of the Magwa and Gudair Formations found to the east of Burgan, when drilling the Ahmadi Ridge, also occurred on the western side of the Burgan axis. The Wara and Burgan Sands at Umm Gudair were water-bearing.

At this time, the condition of the world oil market made it desirable to find a lighter type of crude. The best prospects for doing this seemed to lie in the area north of Kuwait Bay, as it was nearer to the fields of Southern Iraq which, producing from a stratigraphically lower sand horizon than Burgan, produced a crude of higher A.P.I. gravity.

During previous years, reflection seismograph work had been done in the area and a suitable location for a wildcat well was selected from the interpretations of this work. A well, Raudhatain No. 1, was spudded-in on 12th September, 1954, and reached its total depth of 10,301 feet on 12th June, 1955. It proved the existence of a considerable oil accumulation, the actual extent and commercial value of which can only be established by further test drilling.

GEOLOGICAL DESCRIPTION

SOUTH-EAST KUWAIT

Stratigraphical

The stratigraphy of the Kuwait-Basra area has been dealt with exhaustively by Messrs. R. M. S. Owen and Sami N. Nasr [6] in a paper which is now in course of publication by the A.A.P.G. and a summary of their work is given below. The author is indebted to Dr. A. H. Smout of the Iraq Petroleum Company and to Dr. F. E. Eames of the British Petroleum Company for drawing his attention to the results of recent work which may affect the dating of certain of the

formations described. In the first place Dr. Eames, after making long range correlations of fauna round the Indian Ocean, in Peninsular India [4] and in Persia and Iraq, has been led to conclude that *Ostrea latimarginata* is probably restricted to the Burdigalian, although hitherto it has been accepted as indicating the Middle Miocene. Therefore the Zor Formation may be Lower Miocene.

Secondly, Dr. Smout has examined material from the base of the Dammam Limestone which contained an *Operculina*, which he believes may be *O. libyca*. As this form was not associated with the normal *Rhapydionina macfadyeni*, *Alveolina elliptica*, *Nummulites gizehensis* and *N. discorbinus* fauna and the range of *O. libyca* is at present accepted as being Lower Eocene, it is possible that the base of the Dammam and the whole of the Rus may be of Lower Eocene age.

Miocene Pleistocene	
Kuwait Group	
Dibdibba Formation (Pleistocene)	Sands and gravels with subordinate marls. Absent at Burgan, up to 345 feet thick in North Kuwait.
Zor Formation (Middle Miocene)	Anhydrite gypsum, marls and shallow water limestones. Absent at Burgan, 350 feet thick in North Kuwait. *Ostrea latimarginata, Ostrea vestita, Clausinella.*
Ghar Formation (Oligocene - Lower Miocene?)	Sands with subordinate gravels, occasional clays. Up to 470 feet thick. The base lies unconformably on the Dammam Limestone.
Eocene	
Hasa Group	
Dammam Formation (Middle Eocene)	Recrystallised and dolomitised limestones capped by chert in Kuwait and with 7-25 feet of waxy grey green shale at base, about 580 feet thick at Burgan. *Rhapydionina macfadyeni, Alveolina elliptica, Nummulites gizehensis, N. discorbinus.* The bottom beds sometimes contain *Operculina libyca.*
Rus Formation (Middle Eocene?)	Thick bedded anhydrite with subsidiary limestone and marls. About 250 feet thick at Burgan.

Radhuma Formation (Paleocene? - Lower Eocene)	Marly limestones with subsidiary recrystallised and dolomitised limestones thin anhydrites. About 600 feet thick at Burgan. *Rotalia sp., Lockhartia sp.* which occur as a flood about 500 feet above the base of the formation and provide an excellent marker.
Upper Cretaceous	
Aruma Group	
Tayarat Formation (Upper Maestrichtian)	Highly porous, recrystallised reef limestones, interbedded with black pyritic shales. Black shale bed at top. About 450 feet thick. *Omphalocyclus macropora, Loftusia sp., Lepidorbitoides sp.*
Bahra Formation (Upper Maestrichtian)	Grey or buff globigerina marls in the north, grading to white to grey dense microcrystalline limestones with black shales in the lower part in the south. About 350 feet thick. *Globotruncana, Omphalocyclus macropora.* The base of this formation marks a disconformity.
Gudair Formation (Campanian-Senonian)	Dense white detrital limestones with marly pseudo oolites and black shales towards the base. Apparently equivalent to the Hartha, Sa'di Tanuma and Khasib formations of Iraq, with the lower members absent through progressive overlap against the Burgan high. From 50-450 feet thick. *Pseudoedomia complanata* Eames and Smout 1955. [5] *Archaeocyclus midorientalis* Eames and Smout, 1955, and *Rotalia skourensis* Pfender, 1938. The lower contact is always unconformable and represents the wide spread Aruma-Wasia unconformity at the junction between the Upper and Middle Cretaceous.

Middle Cretaceous

Wasia Group

Magwa Formation (Turonian-Cenomanian)	Grey, dense, marly, pyritic limestones and green shales eroded completely from the crest of the Burgan and Magwa fields, increasing in thickness towards the flanks. The maximum penetrated is 434 feet. *Praealveolina cretacea, Oligostegina.*
Ahmadi Formation (Cenomanian)	Green and brown shales in the upper part, which are eroded to a greater or lesser degree over the Burgan structure. Grey shales and marly limestone with *Cythereis bahraini* in the bottom part. Forms the "Cap Rock" over the Burgan, Magwa and Ahmadi fields. Normally from 200 - 250 feet thick but eroded to 80 feet thick over the crest of the Burgan structure. *Exogyra conica, E. columba, Neolobites.*
Wara Formation (Cenomanian)	Interbedded fine grained sandstones and siltstones, often glauconitic, with dark grey shales. Comprises the "First and Second Pays" of the S.E. Kuwait fields, about 180 feet thick and productive at Burgan. Fossils are rare but include *Exogyra cf. columba, Orbitolina, Trigonia* and *Ostrea.*
Mauddud Formation (Cenomanian)	Whitish porous micro-crystalline limestone with abundant *Orbitolina concava.* About 30 feet thick at Burgan.
Burgan Formation (Albian)	Productive in S.E. Kuwait.
Third Sand Member	
Upper	Soft, clean and well sorted sandstones, usually glauconitic with interbedded dark grey shales.
Middle	Pure, medium to coarse grained quartz sand.
Lower	Sandstones, usually glauconitic with interbedded dark grey shales. About 475 feet thick at Burgan.

Fourth Sand Member	Soft, clean and well sorted quartz sand, medium to coarse grained with minor shale breaks and a 20 foot shale at the base. About 675 feet thick at Burgan.
Lower Cretaceous	
Thamama Group	
Shua'iba Formation (Aptian)	Fine grained dolomitic cavernous limestone 200 - 300 feet thick. *rudistae, Orbitolina discoidea, Choffatella decipiens.*
Zubair Formation (Lower Aptian-Barremian)	Interbedded sandstones and shales. Not productive in S.E. Kuwait. About 1,160 feet thick at Burgan.
Ratawi Formation (Neocomian)	Greenish black massive shales.

The relationship of the various formations between a well on the Burgan structure, and one in an area not affected by uplift, is illustrated by the stratigraphic columns for the wells Burgan No. 113 and Umm Gudair No. 1 on Figure 2.

Structural History

The geology of Kuwait is known only from wells drilled and geophysical work completed there. There are no outcrops in which the characters of the rocks penetrated at depth can be studied and deep wells have been drilled only over a small proportion of the total area of the State.

In general, the area from Basra through Kuwait and Al Hasa comprises a series of roughly parallel anticlinal uplifts. Most of these have axes trending north-north-west to south-south-east, but some are lying almost directly north to south and a few from north-north-east to south-south-west. Uplifts have been penetrated by drilling at Gawa, Qatif, Fadhili, Abu Hadriya and Ras Safaniya in Al Hasa, at Wafra in the Kuwait/Saudi Arabia Neutral Zone, at Burgan, Magwa and Ahmadi, Umm Gudair and Raudhatain in Kuwait and at Zubair, Ratawi and Rumaila in Southern Iraq (see Figure 1). Some of these uplifts are now the site of productive oilfields, some do not now contain oil, although they may in the past have done so. Others, which exist as

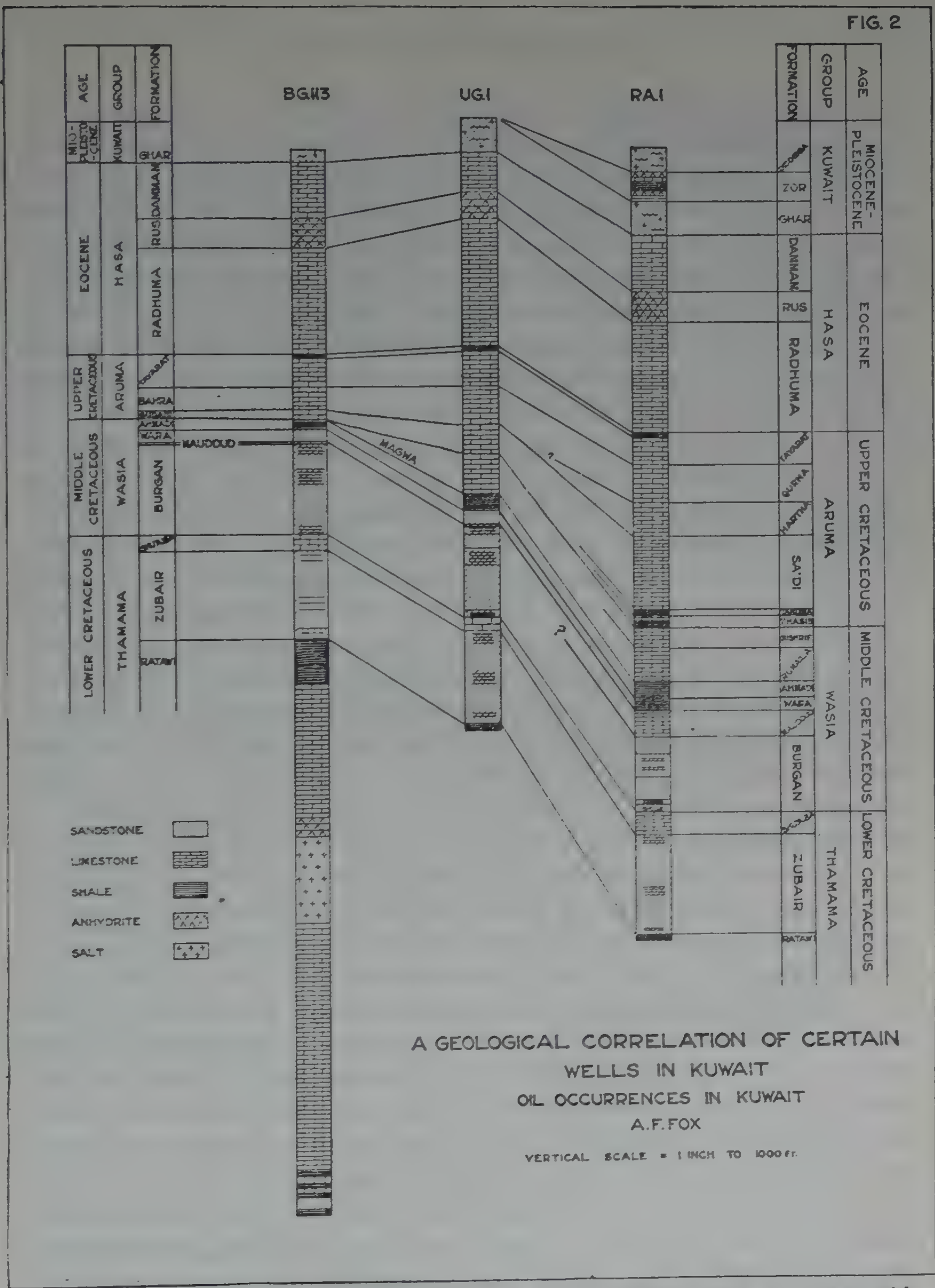

Figure 2. A simplified stratigraphic correlation of a crestal Burgan well (BG. 113) with one off the Burgan Uplift (UG. 1) and a well in North Kuwait (RA. 1). BG. 113 penetrated to 13,853 feet at which depth it was thought to be in the Trias. As no adjacent well has penetrated to an equivalent depth no attempt has been made to correlate or name the formations below the Ratawi. The thick Jurassic evaporite section can however be seen.

structures today, may have experienced all their growth since the date of migration of oil, and therefore do not contain petroleum. Where the Wara, Burgan and Zubair Sands have been penetrated in Kuwait, they have contained small patches of black, heavy, tarry oil. These patchy deposits occur in the sands which are water-bearing and are also found in the oil reservoirs surrounded by lighter oil. It is probably that differential movements are still affecting the structure of the area.

In Kuwait, the Burgan/Magwa/Ahmadi structural complex can be regarded as one unit sharing a common origin, though each part has its own time of formation and special structural characteristics.

The existing structural pattern is an accumulation of a series of movements individually short but collectively of long duration. It is probable that from the end of the Jurassic up to the period in the Cretaceous, represented by the deposition of the Mauddud Limestone, Kuwait and the area surrounding it was relatively stable with sediments being regularly deposited on a sea floor gradually sinking beneath them. Probably, also from the close of the Cretaceous until the end of the Middle Eocene, conditions reverted to stability. Between the deposition of the Mauddud Limestone and the end of the Cretaceous, and between the end of the Middle Eocene deposition and the laying down of the Miocene deposits of the Ghar Formation, the elevations of parts of the Burgan/Magwa/Ahmadi anticlinorium relative to each other, and to their surroundings, changed considerably. These changes in elevation were accompanied by stratigraphic thinning, local washouts and under-water erosion over uplifted parts and by accelerated deposition in temporarily low areas; for instance, on the down-thrown side of faults.

In general, the rise appears to have started in Cenomanian times, but gradually accelerated until erosion replaced deposition over the crest of the structure. The total difference in the thicknesses of Cenomanian rocks between the crest of the Burgan structure and the surrounding sea bed unaffected by uplift is at least 730 feet, part due to stratigraphic thinning, part due to pene-contemporaneous erosion and some probably due simply to non-deposition.

At the top of the Cenomanian the Aruma Wasia unconformity occurs. This wide-spread time-break corresponds to the junction of the Upper and Middle Cretaceous and is particularly prominent in the Burgan/Magwa/Ahmadi area, where pronounced under-water erosion accompanied or followed the uplift of the Middle Cretaceous sediments.

In well sections the unconformity is found marked by the occurrence of localised concentrations of oolitic limonite occurring as smooth, polished, ovoid, round, brown objects which, for convenience, have been named "sporbo". The magnitude of this unconformity decreases towards the north.

In Cenomanian times, structural growth continued when differential movement of more than 275 feet occurred. During this time the Gudair Formation was laid down consisting of Detrital Limestone reflecting the contemporaneous deformation and erosion and having at its top a disconformity, probably indicating a period when the rate of uplift had again induced sub-aqueous erosion over the crests of uplifts.

From the Maestrichtian to the Middle Eocene, there was further growth of the Burgan/Magwa/Ahmadi structural complex in excess of 500 feet with the main focus of uplift steadily moving northwards from Burgan to Magwa.

At the end of the Middle Eocene there was a pause in deposition, rocks of this age being overlain with Miocene or younger sediments. The rejuvenation of the old structures continued, however, though the main uplift was concentrated on the eastern flank under the Ahmadi Ridge.

With this post Middle Eocene movement, the Burgan/Magwa/Ahmadi structure reached its present state of development. An examination of the structural map at Figure 3 shows the present form of the Mauddud Limestone, which is a wide spread structural marker in the area, as evidenced by the various wells which have been drilled into it. It can be seen from this map that the character of the Ahmadi structure is rather different from that of either Burgan or Magwa. The two latter are markedly oval in shape and it is easy to imagine that they have reached their present form through continued uplift. Although this mechanism may also have formed the Ahmadi Ridge, the apparent regularity in the direction of faulting and the definite elongation along the north south axis, points more to a compressive origin for this part of the structure. It is possible, therefore, that the Ahmadi Ridge developed because of compressional stresses felt during the Zagros Orogeny, while Burgan and Magwa acted as a stable block. The cross sections at Figure 4 show the differences in the structures.

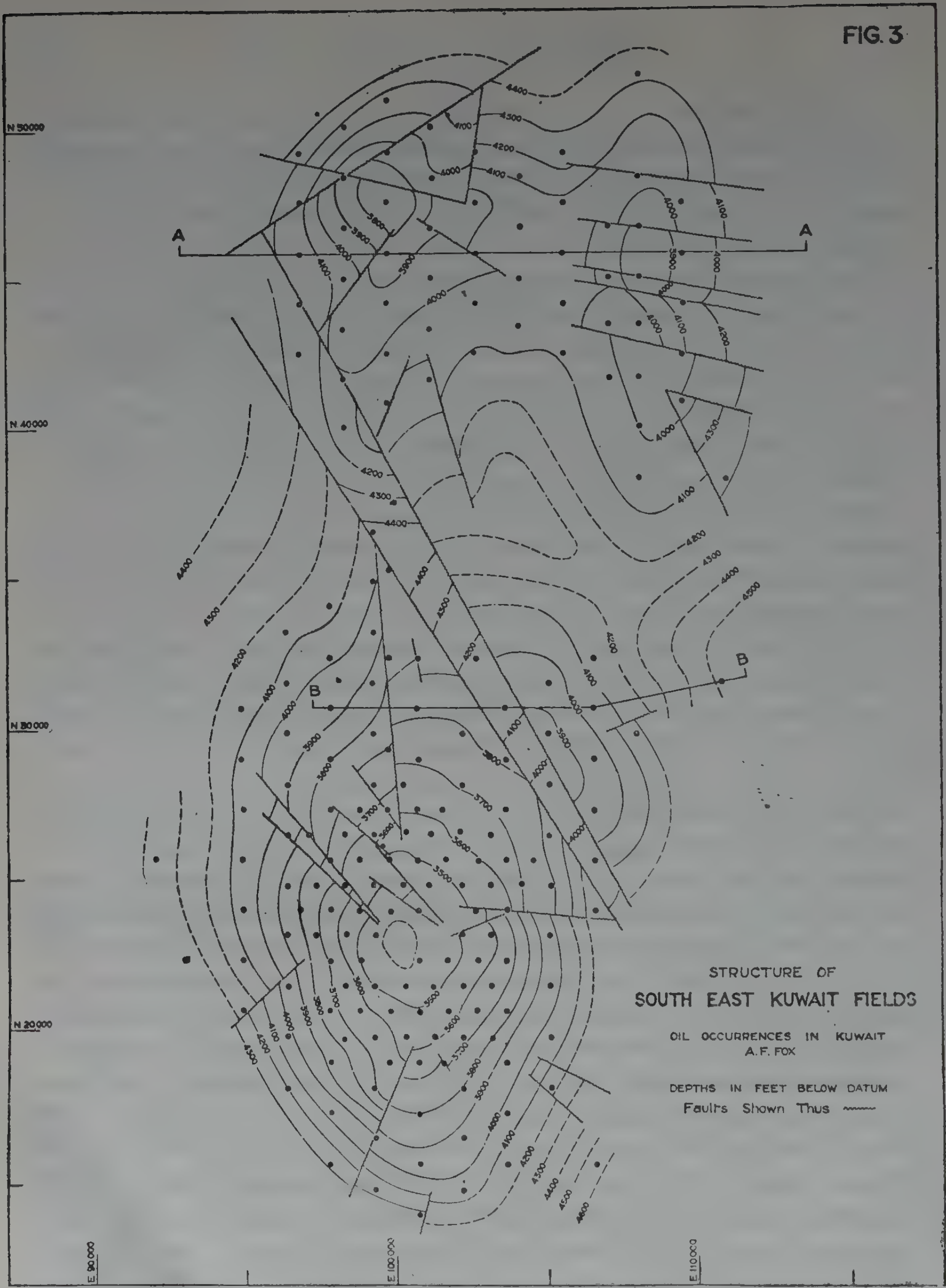

Figure 3. The Structure of the South Eastern Kuwait Oilfields. The stratum contours are drawn on the top of the Mauddud Limestone. Faults shown are those identified in wells or for which other good evidence exists, the direction and extent of all faults is open to question.

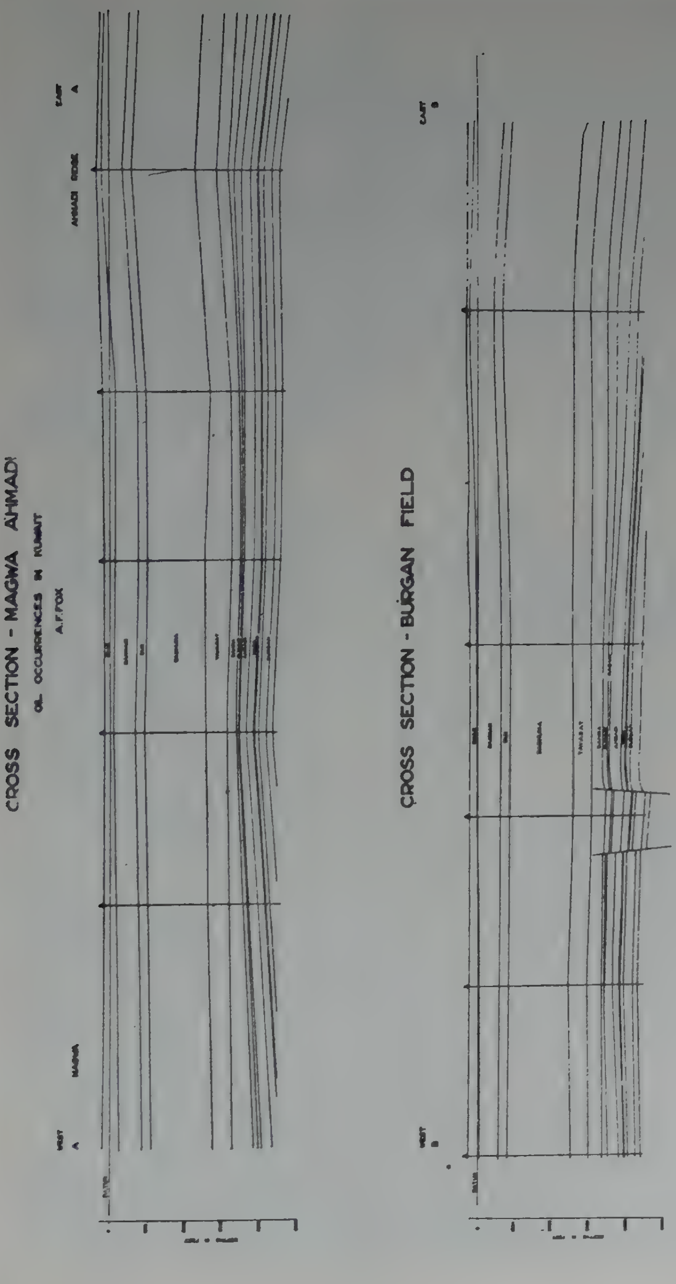

Figure 4. Cross sections illustrating the thickening of the Gudair and Magwa Formations away from the Burgan and Magwa uplifts. The lines along which the cross sections are drawn are shown on Figure 3.

Up to, and during the Cenomanian, local adjustments by normal faulting occurred throughout the area of uplift. Evidence for the presence of faults has been obtained almost entirely from a correlation of electric logs, from which it is possible to identify positions where beds have been cut out. In some few cases, faults have actually been identified from cores and in others faulting can be inferred from sudden changes in dip or strike. This latter evidence, however, is highly conjectural since dips over the Burgan structure rarely reach more than three degrees. Fault evidence has also been obtained from reflection records, although discontinuities inferred by this means have not always been confirmed by drilling. Most of the faults so far identified have throws of the order of 100 feet, though there is a major break running from north-west to south-east, separating the Burgan from the Magwa and Ahmadi fields. Along this break throws of up to 300 feet occur.

Although the presence of faulting can be demonstrated, the orientation and extent of individual faults is practically impossible to determine, since the chance of penetrating the same fault in two adjacent wells at the present density of drilling is extremely small.

In looking for a mechanism which could produce the type of structure found in South-east Kuwait and give rise to the type of structural development described above, the immediate solution of a piercement salt plug comes to mind. Fault patterns very similar to those developed over Burgan and Magwa have been produced experimentally in the laboratory during scale model investigations into the effect of combined uplift and sedimentation. [6]

In drilling Burgan No. 113, a deep test of the Burgan structure, an evaporite series of Jurassic age was penetrated from 8956 to 10,072 feet, which included large quantities of bedded salt (see Figure 2). This evaporite series appeared to replace the Hith Anhydrite and Arab Zone members found in the Neutral Zone and in Saudi Arabia, while the transition from the normal Saudi Arabian succession to a thick evaporite must be very rapid between Wafra and Burgan. It is possible, therefore, that part, at least, of the growth of the Burgan, Magwa and Ahmadi complex has been due to plastic flow in the Jurassic salt and is the expression through the Cretaceous and younger rocks of an incipient piercement salt plug. On the other hand, no

evidence was obtained from the cores in Burgan No. 113 that any flow in the salt had occurred.

However, it is known that the Cambrian includes large salt deposits on the Iranian side of the Persian Gulf, which have subsequently intruded their cover to form the great salt plugs of South Iran.

There is also in the Jebel Sanam, a few miles inside Iraqi territory to the North of Kuwait, what appears to be the surface eruption of a deep seated salt plug. Some of the rocks brought to the surface on this feature are very similar to Paleazoic rocks found in similar situations in Iran and associated with the Hormuz salt.[12]

It is possible, therefore, that the uplift under Burgan is not due to Jurassic but to Cambrian salt and is, therefore, very deep seated in origin.

Structure of Fields

The Burgan field is a huge elongated anticline with its long axis running practically due North-South. The crest and flanks of the structure are broken by numerous faults either single, or double, giving rise to small 'grabens'. These faults affect only the Middle Cretaceous beds, and it is possible that they die out in depth in the thick Burgan or Zubair Formations. In many cases their lateral extent and orientation are still in doubt and can only be confirmed by a greater density of drilling (Figure 3).

The north-east flank of the Burgan structure is broken by two normal faults bounding a graben along which throws of up to 300 feet are known to occur. The wells lying in the graben have abnormal thicknesses of Magwa, Gudair and Bahra beds, so that their low structural position is not apparent from structural markers in the Eocene or Upper Cretaceous. This graben separates the north-east flank from the main structure and this small area exhibits certain production peculiarities which indicate that there is a barrier between it and the main part of Burgan.

The Magwa field is very similar to Burgan, though on a smaller scale. Faulting on the Magwa structure seems to be considerably more intense in both numbers of faults and movement. The faulting on the Magwa structure is also of greater importance in its effect on production practices than is that on Burgan.

The south-east of the Magwa structure is cut by a normal fault down-throwing towards the south-west with two wells south of it showing thickenings very similar to the graben wells of Burgan. It is thought, therefore, that the Burgan graben extends north-westwards and includes these wells.

The Ahmadi structure seems to be a simple folded anticline broken into a series of horst and graben blocks by normal faults running almost uniformly slightly north of west to slightly south of east.

The effect of the continued uplift of the Burgan and Magwa structures on the deposition of the Magwa and Gudair Formations can be seen from the cross sections at Figure 4. The scale of the diagram is unfortunately too small for the variations in thickness of the other beds to be apparent.

The continuance of the thickening in these beds down flank from both Magwa and Burgan under the Ahmadi structure, indicating the later formation of the latter, can also be seen. The minor faulting is omitted on these sections, but the main graben feature is illustrated on the Burgan/Ahmadi section.

NORTH-EAST KUWAIT

Stratigraphy

In general, the stratigraphy of North Kuwait shows greater resemblance to Southern Iraq than to South-east Kuwait. This is particularly noticeable in the Aruma and Wasia groups in which the divisions established at Zubair and Rumaila can be identified at Raudhatain. A summary of the succession of the Upper Cretaceous and for the Mishrif and Rumaila Formations of the Middle Cretaceous in North Kuwait is given below, the remainder of the succession is similar to that already given for South-east Kuwait:

Upper Cretaceous

Aruma Group

Tayarat Formation	As at Burgan, but about 850 feet thick.
Qurna Formation (Upper Maestrichtian)	Globigerinal marl sometimes dolomitic with a rich microfauna including *Bolivinoides draco, Buliminella laevis, Bolivina incrassata, Globotruncana sp.* about 300 feet thick.

Hartha Formation (Maestrichtian - Upper Campanian)	Organic detrital glauconitic limestone with grey marls and green shales. About 300 feet thick. *Pseudoedomia cf. complanata Globotruncana cf. stuarti.*
Sadi Formation (Upper Senonian)	White chalky marly globigerinal limestones about 800 feet thick. *Nodosaria, Palmula, Marginulina, Globotruncana, Gumbelina.*
Tanuma Formation (Upper Senonian)	Black shales with calcareous debris, 120 feet thick. *Monolepidorbis sp., Globotruncana sp. Cristellaria sp.*
Khasib Formation (Senonian-? Lower)	Fine grained marly limestone with interbedded shales. About 150 feet thick. *Globigerina sp., Gumbelina sp., Oligostegina sp.*
Middle Cretaceous	
Wasia Group	
Mishrif Formation (Turonian)	Limonite bed at top, dense organic and detrital limestones, often fresh water. About 450 feet thick. *Multispirina iranensis, Chara sp., Taberina bingistani, Cisalveolina fallax, C. lehneri.*
Rumaila Formation	Fine grained marly limestones and marls at the top, passing into fine grained chalky limestone at base. About 180 feet. *Orbitolina concava var qatarica, Cyclammina whitei, Cyclammina sp., Oligostegina sp.*

Below the Rumaila, the succession becomes similar to that at Burgan except that thicknesses increase considerably. The correlation between the two successions is shown on Figure 2.

Structural

The structural history of North Kuwait has not been worked out in any detail because of lack of sub-surface evidence. At the time of writing one well, Raudhatain No. 1, has been completed at 10,301

feet in the Ratawi Formation, and a second well, Raudhatain No. 2, is drilling on the same structure.

The location for Raudhatain No. 1 was selected after seismic reflection work and, as far as is known, the structure is roughly circular in plan and lies on the same north to south line as the Burgan complex.

From the relationship of the various beds penetrated to their equivalents at Burgan, it appears probable that structural development was later at Raudhatain than it was at Burgan, and it may be that the elevation of North Kuwait structures has been wholly post Eocene.

Structural adjustment in the area between Raudhatain and Basra is still going on [8] but until more sub-surface data is available the length of time it has been going on must remain in doubt.

GEOGRAPHICAL AND GEOLOGICAL DISTRIBUTION OF OIL

Although the quantity of oil production from Kuwait has brought the country into the front rank among world producers, only the Burgan, Magwa and Ahmadi fields have so far been developed, and the presence of oil has only been proved in that area and at Raudhatain in the northern part of the State, and then only in the Wara, Burgan and Zubair Formations.

One exploratory well at Umm Gudair, to the west of Burgan, proved to be a dry hole in the Burgan Sands, but there remains a considerable area still unexplored by the drill. Any conclusions regarding the distribution of oil in Kuwait must, therefore, be tentative. Some general principles can be deduced from the evidence but are applicable only to the Burgan Formation.

The facts from which deductions can be made are briefly:

I) Kuwait itself is on the western side of the Zagros geosyncline. Present geological thought inclines to the belief that oil migration into the Burgan and Wara Sands in Kuwait was from the north-east or east.

II) Structures presently identified lie on what is probably a major structural trend extending from Raudhatain in the north, through Magwa and Burgan to Wafra in the Kuwait-Saudi Arabia Neutral Zone.

III) The distance of migration of the oil into these reservoirs is probably large.

IV) The density of the oil found in the Burgan Formation in each of the fields so far found along the Raudhatain-Wafra line varies with depth. The lightest crude is in each case found at the crest of the reservoir and the heaviest above the water. Sometimes a belt of tar is found immediately above the water.

V) In each reservoir the range of density of the crude appears to be related to its position along the trend. In the north the crest of the Raudhatain structure contains the lightest crude with denser crude beneath it. The crests of Ahmadi, Magwa and Burgan are occupied by successively heavier crudes and Wafra yields the heaviest of all.

Various explanations to account for the gravity differentiation have been advanced, in which the two most favoured mechanisms are either a combination of several different migrations of oil into one reservoir or a segregation of the crude after entering the reservoir. Neither of these is really satisfactory, since the first leaves unexplained the regular increase in A.P.I. gravity according to structural position along the trend, and the second ignores the difficulty of obtaining vertical segregation across impermeable shale breaks within a reservoir, and does not explain why gravity segregation is not apparent in limestone reservoirs. For example, Gatch Saran which is a fractured limestone reservoir has a total oil column of over 4000 feet and, if gravity segregation took place within a reservoir, it would be expected to have occurred there. In fact no difference in the density of crude could be detected between oil produced from the top and from the bottom of the oil column.[9]

It has been noted that segregation similar to that found in South-east Kuwait occurs when crude petroleum diffuses upwards through a tube packed with Fuller's earth.[10] Also certain sands, such as the Tensleep (Pennsylvanian) of Wyoming, have quartz grains which are activated and adsorb the blackest and heaviest components of the crude, allowing the oil to be removed from them afterwards by preferential adsorption of sodium ions from a soda solution.[11]

If either of these mechanisms is applied to crude oil migrating through a sandstone, the effect will be to retard the heavier hydrocarbon molecules so that, instead of an homogenous mixture of all types of hydrocarbon the first crude to pass through the formation will be stripped of its heavy molecules which will be released as a 'tail'

after being flushed off their adsorbing quartz grains by sodium ions from the formation water.

It has been demonstrated that a series of anticline traps, arranged in ascending positions along a structural trend and being traversed by a mixture of gas, oil and water, will selectively entrap the fluids, so that higher proportions of gas are retained in the anticlines which are lowest along the trend.[12]

In the case under consideration and ignoring the effects due to gas, the first structure would become filled with the lightest oil, each succeeding structure along the trend receiving slightly heavier crude. Also, the crude in any one reservoir would be graded from top to bottom, the light, early arriving crude having been relieved of its heavy molecules, filling the crest and lower sections being filled with later arriving, and consequently heavier crude.

Moreover, if the retention of the heaviest hydrocarbons was prolonged until no further oil was migrating through the formations and then ceased, a flood of very heavy oil would form the lowest section of oil in the reservoir, a condition which is found at Burgan.

Although proof of this hypothesis cannot now be, and possibly never will be conclusive, the arrangement of crude between and within the several Burgan Sand reservoirs in Kuwait is in line with it. The hypothesis also provides a useful basis for the direction of exploration for new reservoirs in areas of wide spread sandstone reservoir rocks.

STATISTICAL SUMMARY

During the ten years since the production of crude restarted in Kuwait after the war-time enforced rest, the crude production has become very large. In 1955 no less than 398.6 million barrels of crude oil were obtained from the three producing fields.

In order to reach this figure the drilling effort and all supporting services have been extended to their utmost.

The development of Kuwait as an oil producing country can be summarised by the table at Figure 5, on which the number of wells completed, the footage drilled year by year and the exploration work are shown, together with each year's production.

For more ready reference each section of the table is reproduced graphically in Figures 6, 7, 8 and 9.

STATISTICAL SUMMARY OF KUWAIT OIL COMPANY'S ACTIVITIES IN KUWAIT; 1946-1955

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955
Development Wells Completed	8*	5	24	49	13	19	19	18‡	13	22
Exploratory Wells Drilled	—	—	—	—	—	—	2	1	—	1
Development Footage Drilled	37,665	34,998	122,000	241,771	52,199	77,754	82,949	70,290	56,638	110,439
Exploratory Footage Drilled	—	—	—	—	—	—	12,722	8,017	15,380	2,938
Seismic Traverses Shot Kilometres	—	—	19.3	300.2	225.7	79.3	416.6	719.2	303.9	734.4
Shot Hole Footage Drilled	—	—	3,420	65,566	92,583	32,005	156.477	324,910	292,628	475,458
Crude Production Mill. bbls.	6.0	16.2	46.7	90.2	125.9	205.1	273.4	314.7	347.6	398.6

* Includes wells drilled before 1942.
‡ Includes completion of Burgan No. 1.

Figure 5.

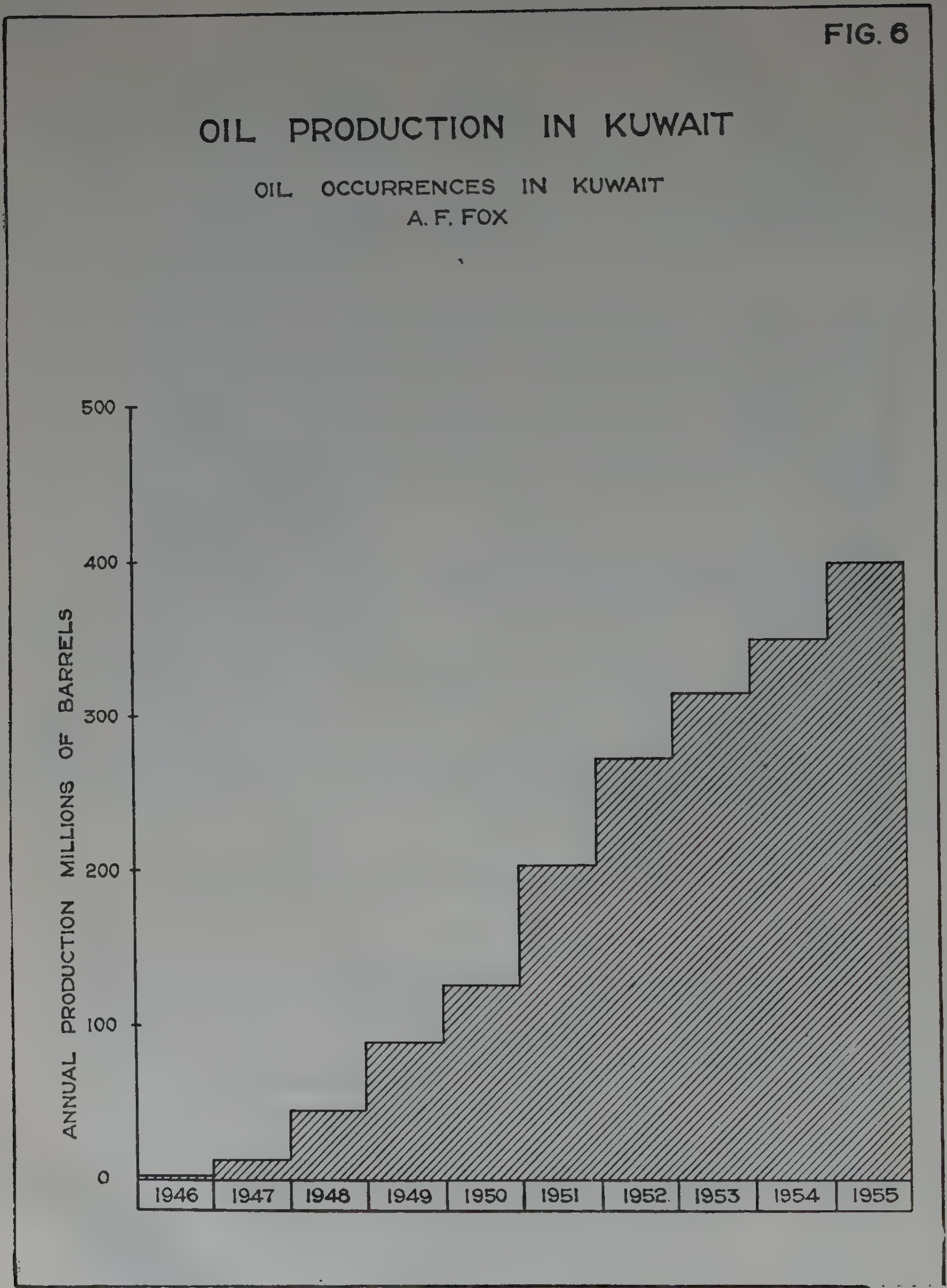

Figure 6. Oil production in Kuwait. Annual totals in millions of barrels.

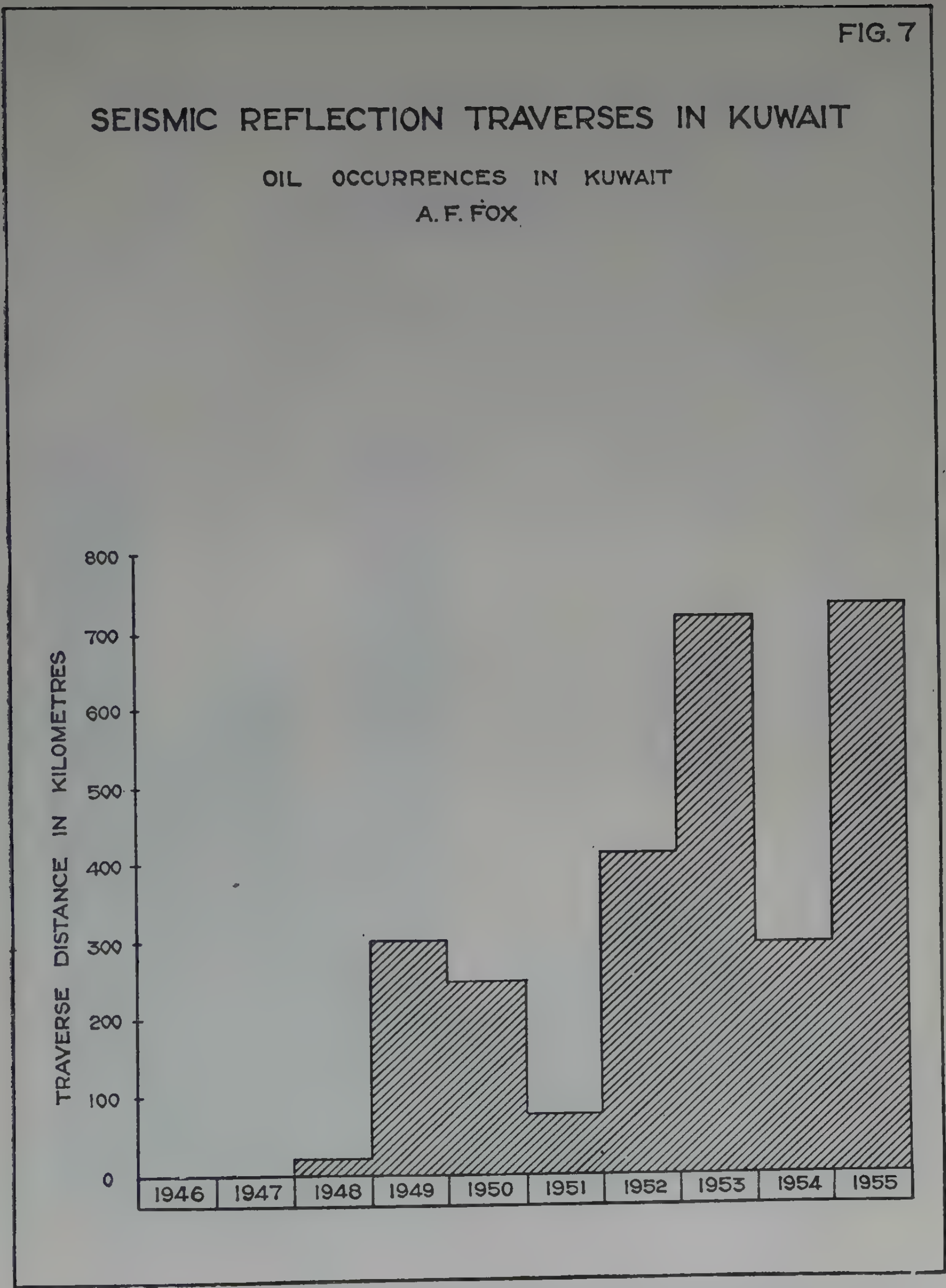

Figure 7. The distances surveyed by Seismic Reflection Surveys since 1946. In 1953 two crews were working and in 1955 one. The increase in rate of traverse is due to the successful development of pattern shooting.

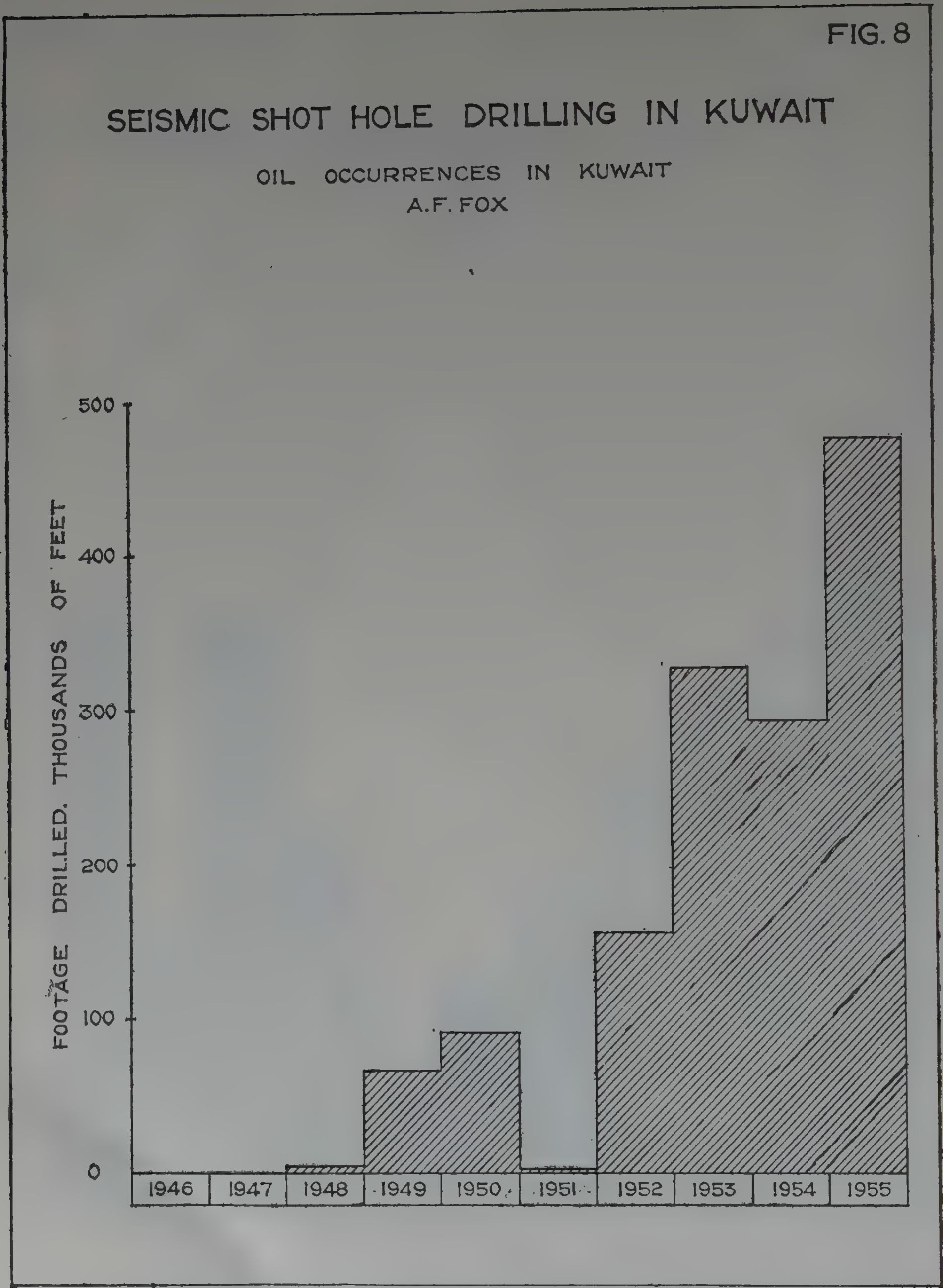

Figure 8. Shot hole drilling footage. The large increase in 1955 over previous years is due to the successful development of pattern shooting with shallow shot holes.

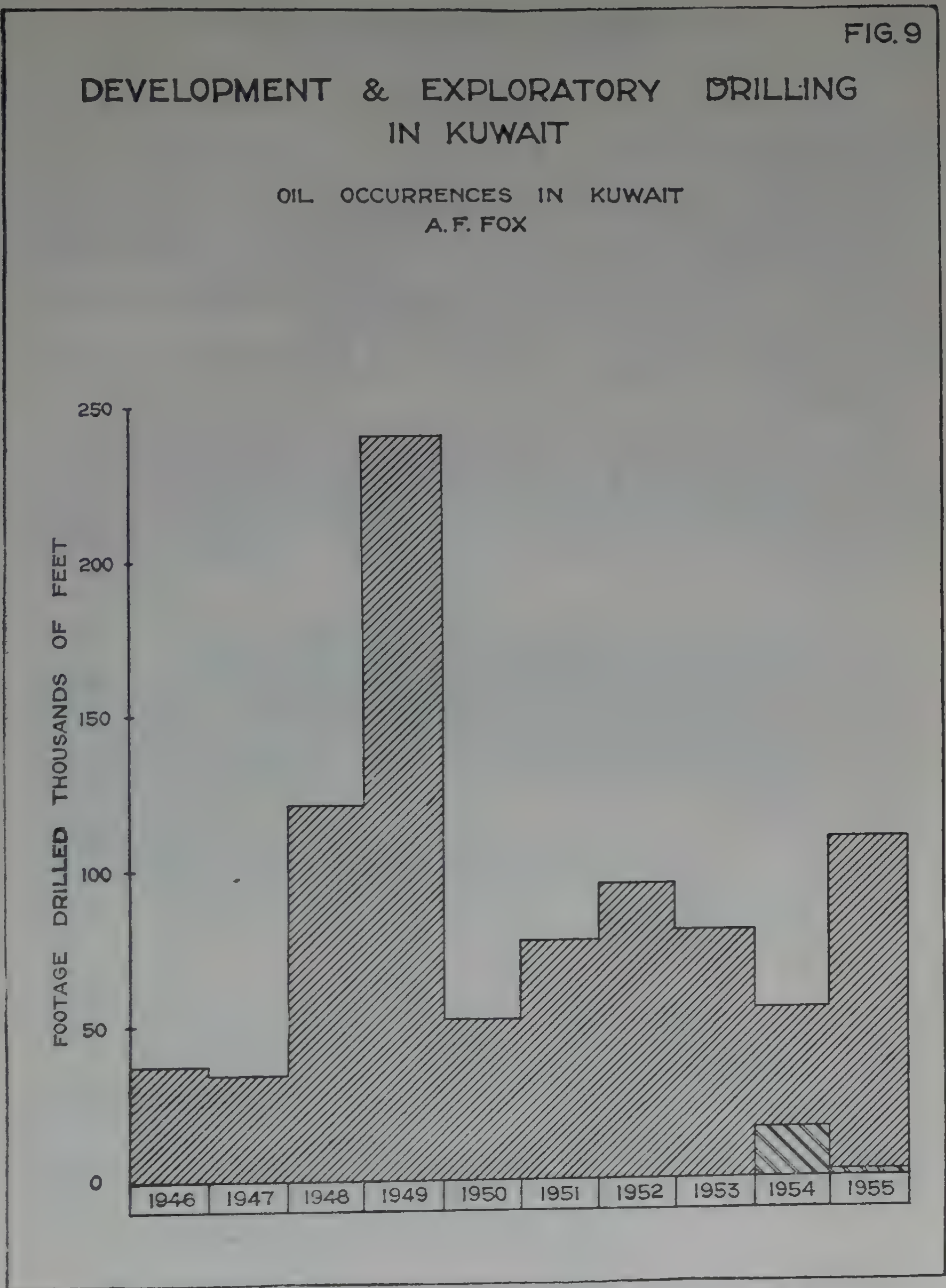

Figure 9. Development and Exploratory Drilling. The peak in 1949 represents the maximum development at Burgan. The area double hatched in 1954 and 1955 represents the exploratory drilling.

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MALAYA

A NOTE ON OIL AND GAS IN MALAYA

By H. E. F. Savage
Deputy Director Geological Survey, Federation of Malaya.

1. Although a large part of the Malay Peninsula has not been mapped in geological detail, it may be stated categorically that the prospects of there being large workable reserves of petroleum at depth are almost non-existent. The reasons for this become manifest when the geology of the country is considered.

2. So far as is known, no Jurassic and Cretaceous sediments have survived in the Federation, and it is doubtful if sedimentation did indeed occur during those times. Furthermore, during the Cretaceous or early Tertiary periods the Palaeozoic strata, comprising Trassic and Carboniferous deposits, were folded, the folding being followed or accompanied by an influx of the granite which now forms the main ranges of Malaya. The Pre-Mesozoic rocks were thus indurated and lost all capacity to retain liquid or gas.

3. Of the two more recent formations, the Quaternary coastal alluvium and the Tertiary, the Quaternary may be discounted as a source of commercial oil because of its youth, its thinness, and the lack of folding necessary to create a large reservoir.

4. The Tertiary beds, unmetamorphosed, containing coal, and of sufficient age to have consolidated into true sandstones and shales, might be looked upon as presenting the properties most conducive to the storage of oil. However, the small size and isolation of its outcrops discourage enthusiasm in this respect, though oil shales in the Batu Arang colliery, near Kuala Lumpur, have yielded mineral oil in the ratio of six gallons of oil per ton of shale.

5. Over twenty reports of oil seepage have been investigated by the Geological Survey of the Federation during the past fifty years, but

these were largely proved to be the results of 'salting', seepage of anti-malarial oil, or misinterpretations by laymen of phenomena of no special significance.

6. As a matter of routine prudence, in the absence of detailed geological maps, the Geological Survey thoroughly investigates every report submitted to it by those who have, or imagine they have, grounds for supposing that large quantities of petroleum exist in the Federation.

QATAR

SYMPOSIUM ON THE GEOLOGICAL OCCURRENCE OF OIL AND GAS

By the Staff of Qatar Petroleum Co. Ltd.

ABSTRACT

Qatar peninsula juts out from the coast of Arabia into the Persian Gulf. Politically it is an independent Arab state under a ruling Sheikh. A concession covering oil and gas rights under the mainland and territorial waters has been granted to Qatar Petroleum Co. Ltd., and under the "offshore" waters or "continental shelf" to Shell Company of Qatar.

The surface geology consists of Eocene rocks with scattered patches of thin Miocene, and of recent windblown sand.

The Dukhan anticline stretching for 80 Km. (50 miles) along the western coast, is the only oil-bearing structure known. It is productive for the northern 50 Km. (31 miles) and over an average width of 4½ Km. (3 miles). Depth of wells varies from 1707 to 2035 m. (5600 to 6600 ft.).

Production is from the No. 3 and No. 4 Limestones of Upper Jurassic age (equivalent to the "C" and "D" limestones of Aramco's "Arab zone"). The No. 3 limestone produces undersaturated oil of 37° API; the No. 4, below and separated from the No. 3 by some 19 m. (60 ft.) of anhydrite, has a large free gas-cap and produces saturated oil of 42° API. Total production was about 5⅓ million tons in 1955. The crude is pumped through a 14½ inch pipeline to Umm Said on the eastern coast and shipped from there.

Two wells have been drilled in the middle of the peninsula, but no further oil has been found as yet.

GEOGRAPHICAL DISTRIBUTION OF OIL AND GAS

Qatar is a small independent Arab state occupying the peninsula of that name which juts out into the Persian Gulf from the Arabian coastline.

The oil and gas rights in the whole of the land area and the territorial waters have been granted under concession to the Qatar Petroleum Co. Ltd. (Barber, 1948; Longrigg, 1954). Similar rights in the "offshore waters" or "continental shelf" are now held under

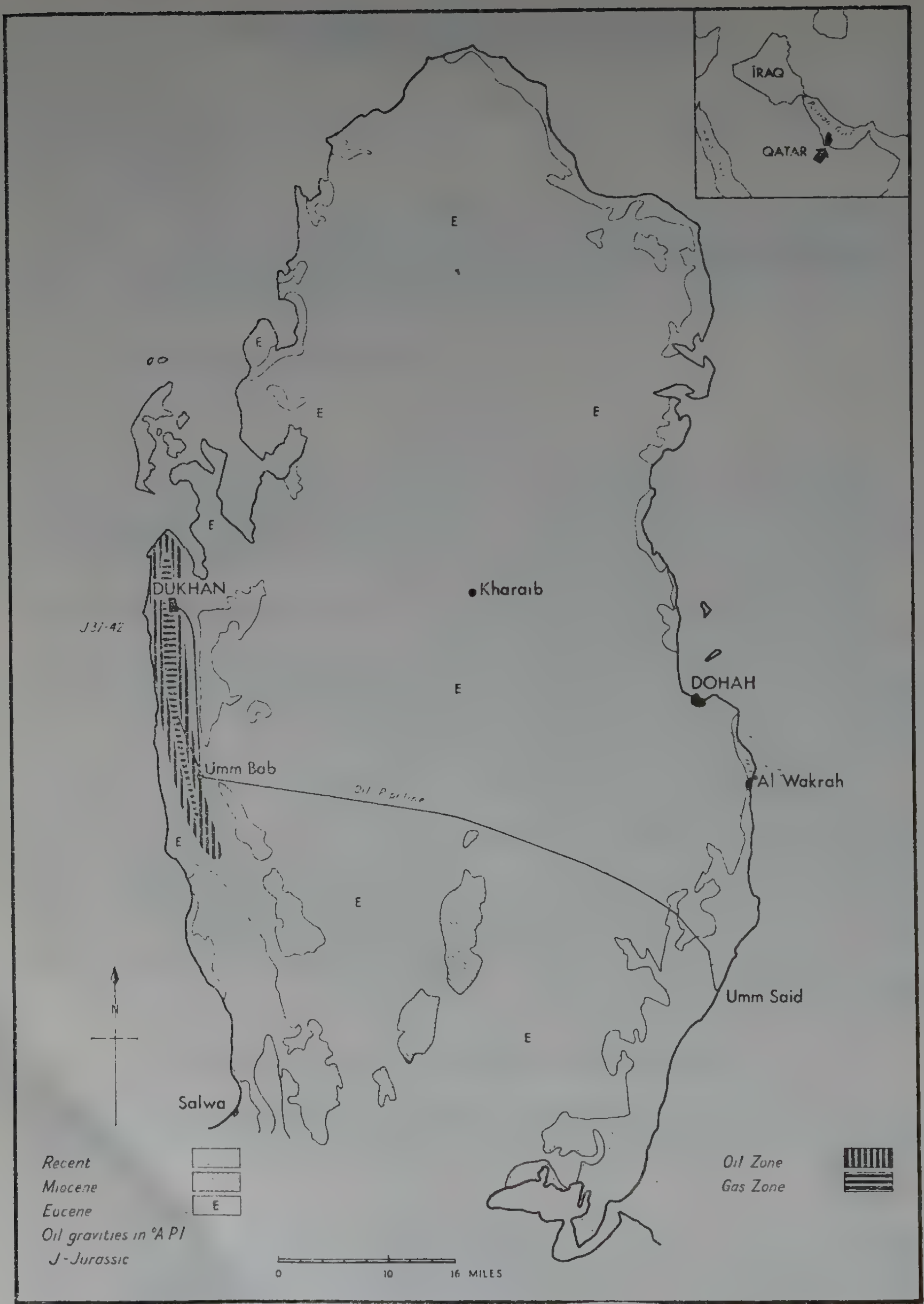

Plate I—Geological Map of Qatar showing Localities.

concession by the Shell Company of Qatar (Longrigg op. cit.; Heater, 1955).

The territory seems geologically to be an extension eastwards of the stable shelf of Arabia.

One oilfield, Dukhan, has so far been discovered. It underlies a surface anticline running down the western side of the peninsula for some 80 Km. (50 miles), the northern 50 Km. (31 miles) being productive.

Two reservoirs are producing oil; the No. 3 Limestone produces undersaturated oil of 37° API; the No. 4 limestone, below and separated from the No. 3 by 19 metres (60 ft.) of anhydrite, has a large free gas-cap above saturated oil of 42° API. These reservoirs are of Upper Jurassic age.

The map (Plate 1) shows localities and areal gelogoy.

GEOLOGICAL DESCRIPTION

The Qatar peninsula is a low flat stony desert. The surface geology consists of Eocene limestones and marls with scattered patches of thin Lower Fars (Miocene). Windblown sand, though present almost everywhere, is only heavy in the south and southeast. The Dukhan structure forms a gentle rounded ridge often broken into mesas. Surface dips are 4° or less (Wellings, 1953; Daniel, 1954).

The cross section of the Dukhan anticline (Plate II). and the log of Dukhan well No. 48 (Plate III) illustrate the general geology. One of two wells drilled in the middle of the peninsula, Kharaib No. 1, penetrated deeper than Dukhan No. 48 and went into rocks of probabale Lower Jurassic age: these are multicoloured shales with minor sands. Above, the Middle Jurassic is predominantly limestone, often dense and of 'chemical' type, but sometimes pellety, oolitic, or dolomitic and having in the lower part sporadically abundant nodules and thin beds of anhydrite. Overlying it comes some 355 m. (1100 ft.) of fine-grained, sometimes rather argillaceous, limestone; above which lies the Riyadh group (Arkell, Bramkamp and Steineke, 1952) or "Arab zone" (Kerr, 1953) of earlier oilfield literature ("Zekrit" of Barber, 1948); this is the section of commercial importance containing the productive Nos. 3 and 4 limestones (equivalent to the "C" and "D" limestones of Aramco's Dammam and Abqaiq fields) underlying the Hith anhydrite. Above this is a thick sequence of rather non-

distinctive finegrained limestones, the lower beds of which are probably still of Jurassic age. The overlying strata, as shown in the well log (Plate III) are not of great interest, the clastic sediments of Middle Cretaceous age which yield commercial production in Bahrein, being water-bearing in Qatar.

The stratigraphy both as whole and in detail shows remarkable similarity from Kharaib to Dukhan and to Bahrein in the north and Dammam and Abqaiq in the northwest.

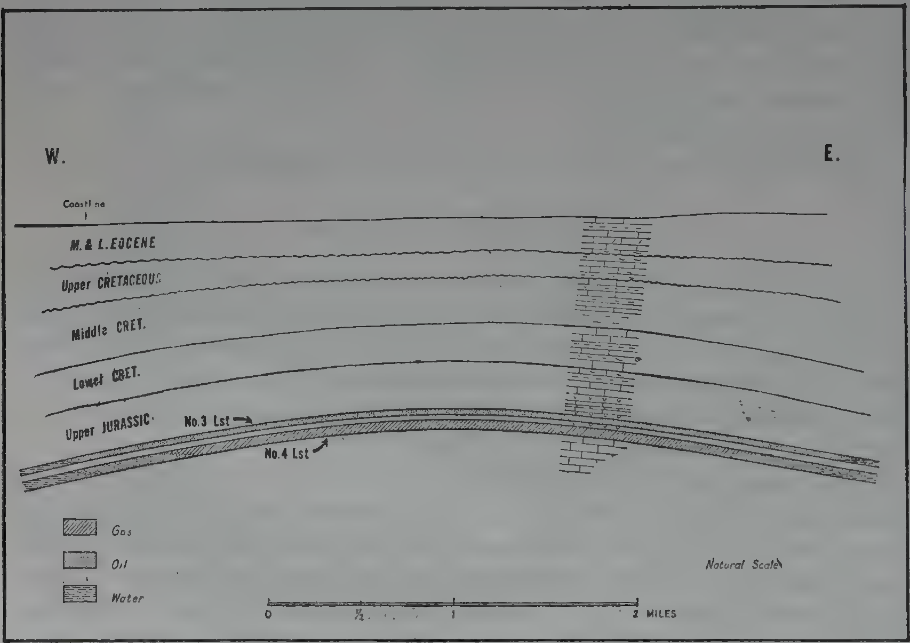

Plate II—Structural Cross Section of Dukhan Anticline.

The Dukhan anticline is believed to have been growing from Jurassic times onwards as there is persistent thickening of formations downflank: its late phase of growth is certainly post-Middle Eocene since Lower Fars formation fingers into synclinal regions of the peninsula.

Commercial production is obtained from the No. 3 and the No. 4 Limestones of Riyadh group. The No. 3 averages about 24 m. (80 ft.) in thickness and is a shelly and pellety limestone. It is overlain by anhydrite with occasional thinner limestones passing up into the Hith

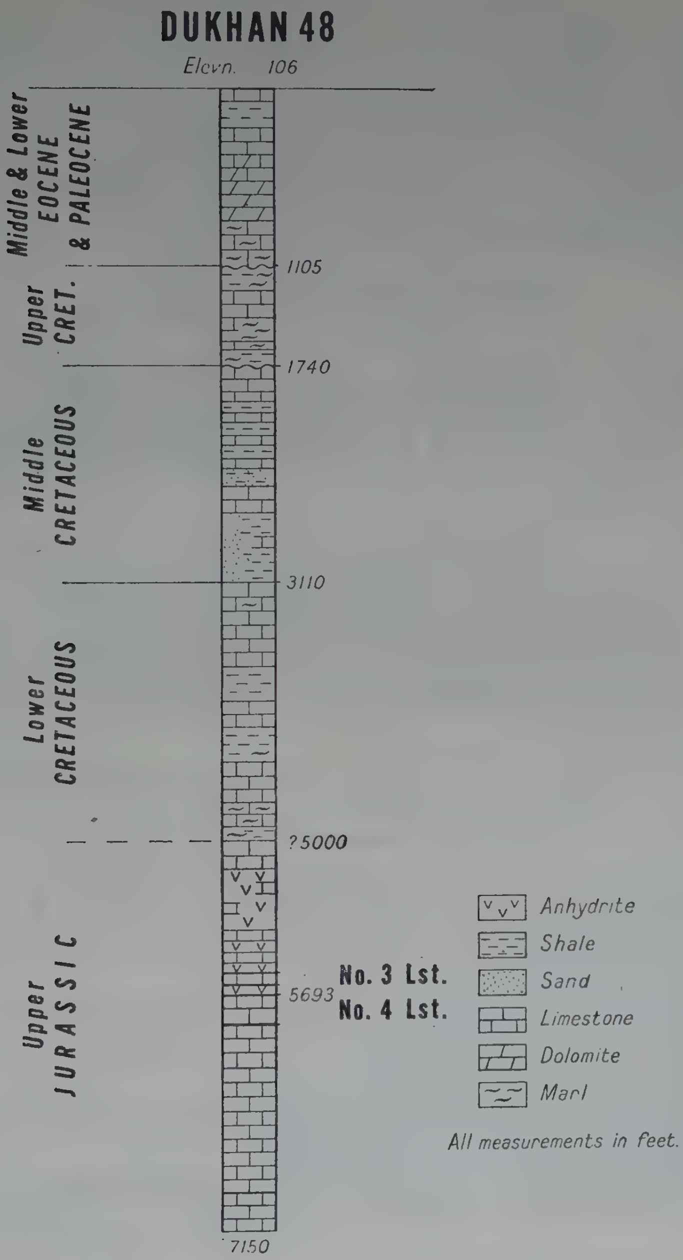

Plate III—Geological log of Dukhan well No. 48.

anhydrite. Below it is another anhydrite 19 m. (60 ft.) thick, which evidently forms a perfect seal since the No. 3 contains under-saturated oil of 37° API while the No. 4 oil, below a large free gas-cap, is 42° API and fully saturated. The No. 4 Limestone is about 56 m. (185 ft.) thick and is also a shelly and pellety limestone, in parts highly dolomitic, with rather better porosity and higher and more consistent permeability than the No. 3.

PRODUCTION CONDITIONS IN THE FIELD

Dukhan field

This is a limestone field in which production is drawn from two main reservoirs, the No. 3 and the No. 4 Limestones. The overlying Nos. 1 and 2 limestones are thin and unproductive, with poor porosity and permeability.

The No. 3 Limestone is some 800 feet thick, of which the upper 65 feet is porous but somewhat impermeable. Although this section contains the bulk of the reserves, the lower part of the limestone, which shows permeabilities of 150 m.d., contributes 80 to 85% of the total oil produced. The limestone is sparsely jointed but otherwise unfractured, and has petro-physical characteristics resembling those of a sand field.

There was no primary gas-cap, the oil being under-saturated with a G.O.R. of about 700 cu.ft./bbl. The gravity is 37° A.P.I.

The main producing mechanism is oil expansion, possibly assisted by a feeble water-drive.

The No. 4 Limestone, lying 60 feet below the No. 3 is 175-190 feet thick and has a mean porosity of 18% and a mean permeability of 65 m.d.

The crude, which is somewhat lighter than that of the No. 3 Limestone, with a gravity of 42° A.P.I., is fully saturated and has a G.O.R. of 1200 cu.ft./bbl.

The underlying water-table is tilted, being about 100 feet higher on one flank than on the other.

The principal producing mechanism in this reservoir is gas-cap expansion, with little evidence of water-drive.

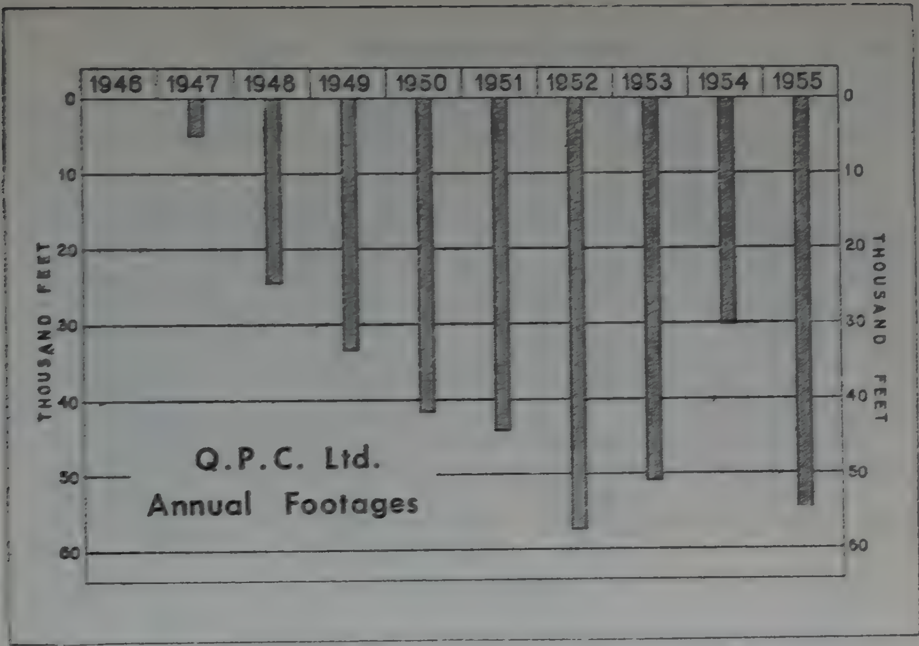

Plate IV—Q.P.C. Ltd. Annual Drilling Footage.

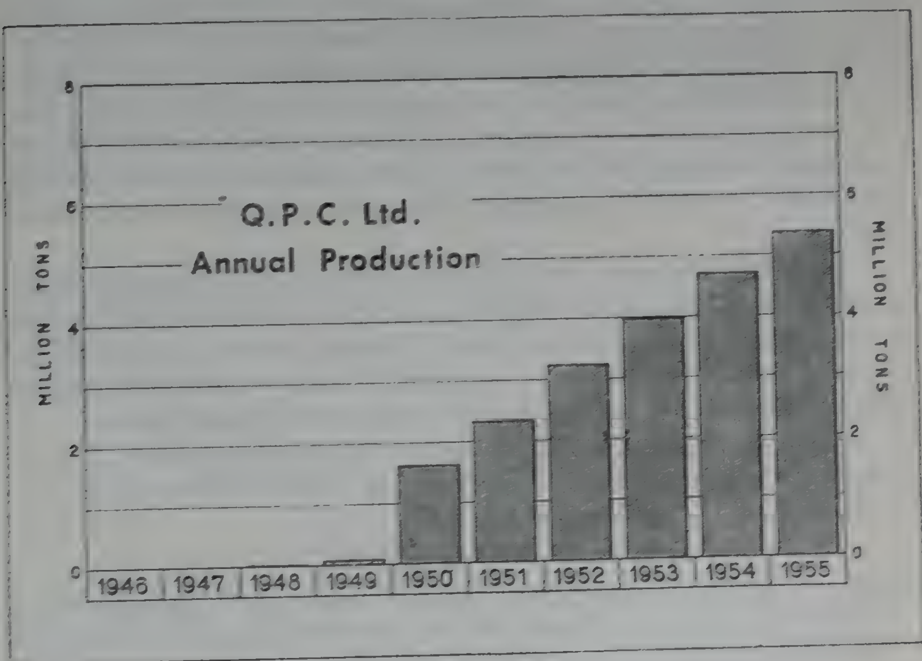

Plate V.—Q.P.C. Ltd. Annual Oil Production.

DRILLING AND PRODUCTION STATISTICS

Drilling footage		*Production-Tons.*	
Year	*Q.P.C.*	*Year*	*Q.P.C.*
1946	——	1946	——
1947	4,884	1947	——
1948	24,452	1948	8,618
1949	33,378	1949	80,307
1950	41,647	1950	1,616,598
1951	44,173	1951	2,332,214
1952	57,271	1952	3,245,343
1953	50,835	1953	3,997,926
1954	30,017	1954	4,704,422
1955	54,720	1955	5,361,778

EXPLORATION HISTORY

Reconnaissance geological survey was made in 1933, and the Dukhan anticline recognised. In 1937-38 the structure was mapped in detail. The first test well found oil in the No. 3 Limestone in 1939, and two more wells were drilled before operations were suspended as a result of the war. Drilling was resumed in 1947, and some 53 wells have now been completed, the majority to tap the No. 4 Limestone.

Two wells have been drilled at Kharaib in the middle of the peninsula, the deepest to the Lower Jurassic: both unfortunately proved dry. They showed the stratigraphy to be almost identical with that at Dukhan.

The whole peninsula has been covered by gravity survey, and the northern three-quarters by magnetic survey as well. Seismic survey has been carried out over the entire Dukhan structure, and local experimental surveys have been made over areas in the north central part of the peninsula, and in parts of the eastern coastal region.

A total effort of some 10 crew months for gravity, and 12 crew months for seismic, during 1947-49 and in 1952, has been made.

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SYMPOSIUM SOBRE YACIMIENTOS DE PETROLEO Y GAS

2ª PARTE DEL TOMO II

OCEANIA

AUSTRALIA

NUEVA CALEDONIA (NOUVELLE CALÉDONIE)

PAPUA Y NUEVA GUINEA (AUSTRALIAN TERRITORY OF PAPUA AND NEW GUINEA)

OCEANIA

AUSTRALIA

GEOLOGICAL OCCURRENCE OF OIL AND GAS IN AUSTRALIA [1]

By M. A. CONDON [2]

ABSTRACT

Although commercial production of petroleum has not been obtained in Australia to date, the occurrence of basins with marine sediments suggests a likelihood of its discovery.

The stratigraphy and structure of the sedimentary basins are described and the petroleum possibilities of each is assessed.

Exploration of all kinds is being undertaken at present and this has resulted in the discovery of one flowing well —Rough Range I.

GEOGRAPHICAL DISTRIBUTION OF SEDIMENTARY BASINS

The outlines of the main sedimentary basins of Australia are shown in Plate 1. The Bonaparte Gulf Basin covers the eastern shores of Joseph Bonaparte Gulf in northeastern Western Australia and north-western Northern Territory. The Canning Basin, of which the north-eastern part is called the Fitzroy Basin, occupies a roughly rectangular area between the Kimberley block and Pilbara block of Precambrian rocks. The Carnarvon stretches from Onslow to the Murchison River along the coastal area of north-western Western Australia. The Perth Basin stretches from Geraldton on the central west coast along the coastal plain to the south coast. The Eucla Basin occupies a large crescent-shaped area at the head of the Great Australian Bight in Western Australia and South Australia. The Murray Basin occupies an area on either side of the Murray and Darling Rivers from the coast upstream for about 200 miles. The Gippsland Basin occupies a narrow coastal

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M.A.Condon—"Oil and Gas in Australia"
SEDIMENTARY AREAS OF AUSTRALIA AND NEW GUINEA.
SCALE OF MILES
200 0 200 400 600
PAPUA-NEW GUINEA
BONAPARTE GULF BASIN
ORD RIVER BASIN
FITZROY BASIN
CANNING BASIN
NORTHERN TERRITORY
GEORGINA BASIN
CARPENTARIA BASIN
LAURA BASIN
QUEENSLAND
BOWEN SYNCLINE
GREAT ARTESIAN BASIN
MACKENZIE BASIN
ROMA SPRINGSURE BASIN
MARYBOROUGH BASIN
WESTERN AUSTRALIA
CARNARVON BASIN
TERRITORY
SOUTH AUSTRALIA
EUCLA BASIN
FROME EMBAYMENT
PERTH BASIN
IPSWICH CLARENCE BASIN
NEW SOUTH WALES
MURRAY BASIN
SYDNEY BASIN
VICTORIA
GIPPSLAND BASIN
TASMANIA
o = AREAS OF TEST DRILLING FOR OIL 1946-1955.
Bureau of Mineral Resources, Geology and Geophysics Jan 1956.
G27-25x

plain in eastern Victoria. The Sydney Basin stretches from the Hunter Valley in the north to south of the Shoalhaven River in the south and for about 50 miles inland. The Ipswich-Clarence Basin stretches from near Brisbane to the Clarence River in northern New South Wales. The Maryborough Basin is a small basin occupying the coastal area south of Maryborough, Queensland. The Great Artesian Basin and its off shoots, the Bowen Basin, the Springsure Basin, the Carpentaria Basin, the Dawson Basin and the Frome Embayment, occupy a very large area in western Queensland, northwestern New South Wales, southeastern Northern Territory and northeastern South Australia. There are other basins of minor importance in northern Western Australia, Northern Territory, coastal north Queensland, coastal western Victoria, South Australia and Tasmania.

STRATIGRAPHY AND STRUCTURE OF THE SEDIMENTARY BASINS

Bonaparte Gulf Basin: Lower Cretaceous radiolarite 50 feet thick and possibly Upper Jurassic plant-bearing sandstone 50 feet thick unconformably overlie older rocks. Permian marine fossiliferous sandstone and siltstone and plant-bearing sandstone in the northern part of the basin rest unconformably on Precambrian basement. In the southern part of the basin, fossiliferous marine Upper and Lower Carboniferous sandstone and limestone total about 2000 feet thick. Fossiliferous marine Upper Devonian sandstone, limestone and shale total possibly 6000 feet in thickness. Fossiliferous Ordovician glauconitic sandstone at least 400 feet thick conformably overlies Upper Cambrian fossiliferous glauconitic sandstone about 600 feet thick. Fossiliferous Middle Cambrian limestone, shale and sandstone 600 feet thick overlie volcanics presumably of Lower Cambrian age.

Regionally, the continental part of the basin is an asymmetrical north-plunging syncline, with Cambrian to Permian exposed on the southwestern flank, but only Permian on the east flank. Major structures are fault-controlled synclines. Strike-faulting is common in the pre-Permian strata.

Canning Basin: Cretaceous sandstone about 100 feet thick is known only from the central part of the basin. Jurassic sandstone thinly covers much of the main part of the basin south of the Fitzroy Basin; 1800 feet of Jurassic shale and sandstone occur in the Broome area. The

Jurassic unconformably overlies the Permian. Triassic sandstone and shale up to 1100 feet thick occupy synclines in the Permian of the Fitzroy Basin; Upper Permian sandstone up to 3000 feet thick occurs throughout the basin. Middle Permian fossiliferous siltstone and sandstone up to 2200 feet thick, and sandstone up to 1300 feet thick crop out in the Fitzroy Basin and on the southeastern margin of the Canning Basin; Lower Permian glacial marine sediments crop out in the Fitzroy Basin and at the southern margin of the Canning Basin; they rest unconformably on Devonian in the Fitzroy Basin and on Precambrian at the southern margin. Upper Carboniferous siltstone, shale and sandstone have been discovered by drilling at Grant Range (Fitzroy Basin). Lower Carboniferous calcilutite 600 feet thick outcrops on the northeastern margin of Fitzroy Basin. Upper Devonian calcareous sediments 3600 feet thick with, in places, interfingered conglomerate and Middle Devonian organic limestone 1850 feet thick are exposed only on the northeastern margin of Fitzroy Basin. A small outrop of Ordovician dolomite and fossiliferous calcilutite and siltstone about 2800 feet thick occurs near the northeastern margin.

The Canning Basin is a large syncline plunging gently to the west-northwest. Within this large unit there are smaller synclines (the northernmost being the Fitzroy Basin) separated by anticlinal ridges. Only the Fitzroy Basin is well exposed; the other parts are generally covered by sand and superficial formations. Evidence is accumulating that the major structural control is the shape of the Precambrian floor and that most of the structures are depositional. Of the large anticlinal structures in the Permian, some are in areas of positive residual gravity anomaly and conformable subsurface structure indicated by seismic survey; others are not conformable with basement highs and may be developed over hills in the Pre-Permian sediments.

Carnarvon Basin: Lower Miocene calcarenite and calcilutite up to 1,500 feet thick are deposited in a wedge along the coastal area; they are unconformable on Middle Eocene calcarenite up to 200 feet thick and Palaeocene calcarenite 200 feet thick. This is unconformable on Upper Cretaceous calcarenite and calcilutite up to 250 feet thick which extends from the coast to 70 miles inland. Lower Cretaceous shale, siltstone, radiolarite, and sandstone up to 2500 feet thick extend from the coast to 100 miles inland. They are conformable on Cretaceous-Jurassic siltstone in the Cape Range area and unconformable on Permian in

the eastern part, on Precambrian in the northeastern part and on? Devonian in the southern part. Middle Permian fossiliferous marine siltstone, sandstone and calcarenite up to 9000 feet thick outcrop in the eastern part of the basin from the Lyndon River for 200 miles southward. Lower Permian marine glacial sediments up to 5000 feet thick, disconformable under the Middle Permian, crop out generally to the east of the middle Permian and extend to the south for another 100 miles; they are unconformable on Precambrian at the northeast, east and southeast margin and on? Lower Palaeozoic at the southern margin. Lower Carboniferous greywacke and fossiliferous limestone up to 2500 feet thick crop out only on the east margin where they are conformable on Devonian. Devonian greywacke, sandstone and fossiliferous marine calcarenite up to 4900 feet thick in the east margin of the basin are unconformable on Precambrian. In the coastal area, Devonian shale, fossiliferous limestone and sandstone 2600 feet thick were cut by Pelican Hill Bore near Carnarvon. Sandstone and siltstone about 4000 feet thick on the lower Murchison River may be of Devonian age. It is unconformable below the Lower Cretaceous and rests unconformably on Precambrian. A sequence of sandstone, siltstone and limestone 4000 feet thick in the southeastern corner of the basin may be of lower Palaeozoic age; it is unconformable below Lower Permian glacial sediments and unconformable on Precambrian.

The Carnarvon Basin includes two long synclinal areas separated by a basement ridge which crops out in the Corrandibby Range. Depositional structures are dominant over tectonic, although the relief of the basement floor has been increased by synclinal down-warping. Anticlinal structures in the coastal area are probably produced by deposition over hills in older sediments.

Perth Basin: In the coastal southern part of the basin, Quaternary calcarenite up to 500 feet thick rests unconformably on Eocene fossiliferous shale 700 feet thick. The Eocene is not known in outcrop but was cut by bores in the Perth area. Upper Cretaceous calcarenite and greensand about 200 feet thick crop out in the north-central part of the basin; Lower Cretaceous shale about 800 feet thick was cut in the Perth bores. Lacustrine and marine Jurassic outcrop on the northern and north-eastern margins, unconformable on Permian and Precambrian. Middle Permian marine shale, coal measures and marine calcarenite 1250 feet thick and Lower Permian glacial sediments 2450 feet thick

crop out only in the north-eastern part of the basin. Ordovician corals have recently been discovered by A. A. Opik and J. Gilbert-Tomlinson in the Yandanooka Group previously believed to be Precambrian. This sequence of shale, tuff, greywacke and limestone 2350 feet thick crops out intermittently along the eastern margin of the basin, unconformably on the Precambrian schist and granite. Seismic sections indicate that the Ordovician sequence dips steeply under the basin and that sediments between Permian and Ordovician may be expected abutting the Ordovician at the eastern side but nearly conformable with it in the central part of the basin.

The Perth Basin is a long syncline with axis near the present coastline. Outcrop is restricted to the eastern margin and northern plunge. Reconnaissance gravity surveys indicate a large negative gravity anomaly. That this is caused by great thickness of sediments has been confirmed by seismic surveys. Anticlinal structures have been indicated by the seismic survey.

Eucla Basin: Lower Miocene marine limestone about 200 feet unconformably overlies Eocene marine limestone of about the same thickness. This unconformably overlies Lower Cretaceous shale, siltstone and sandstone about 400 feet thick and this overlies, probably unconformably, shale and siliceous rock, possibly of Palaeozoic age, 540 feet thick. This unconformably overlies Precambrian basement.

The regional dip is very gentle centripetal from the margin. No anticlinal structures are known.

Murray Basin: In the southwestern part of the Murray Basin, Oligocene limestone up to 2256 feet thick overlies at least 5330 feet of Eocene and Palaeocene sand, conglomerate and lignite with thin marine fossil beds. Cretaceous lacustrine siltstone, sand and gravel up to 820 feet thick and Jurassic lacustrine arkose and siltstone up to 3030 feet thick have been discovered in a few bores. The Mesozoic sediments rest unconformably on indurated and intruded Palaeozoic sediments and granite.

The sequence thickens greatly in the coastal area near the Victoria-South Australia boundary. Many step faults and folds associated with them are known.

In the northeastern part of the basin, upper Tertiary calcareous sediments up to about 850′ thick overlie lignitie sands probably of Eocene age up to about 540′ thick.

In the eastern-most part of the basin, thin Tertiary sediments unconformably overlie Permian coal measures and glacial sediments, which rest unconformably on strongly folded lower Palaeozoic sediments and granite. Very little is known of the structure of the northeastern part of the Murray Basin.

Gippsland Basin: About 1200 feet of upper Tertiary calcarenite and sandy marl are separated from Eocene lignitic sand by a glauconitic sand about 30 to 40 feet thick. This sand contains a heavy viscous oil but no profitable production has been obtained.

Structurally, the Gippsland Basin is mainly a homocline dipping at a very gentle angle out to sea. Recent gravity and seismic surveys have indicated anticlinal structures which are being drilled.

Sydney Basin: Triassic shale, sandstone, siltstone and conglomerate about 3500 feet thick overlie Permian marine glacial siltstone and coal measures up to about 14,000 feet thick. No good source beds or reservoir beds are known.

Regionally, the structure is broadly basinal with several large anticlinal folds.

Ipswick-Clarence Basin: Jurassic sandstone, conglomerate, siltstone, calcareous shale, with thin coal seams, ranging from 3,370 to 6000 feet thick overlie Triassic coal measures 750 to 4000 feet thick.

These Mesozoic sediments occupy a long syncline with a basement of Palaeozoic orogenic rocks.

Maryborough Basin: Cretaceous paralic sediments about 5600 feet thick, and including coal seams, overlie volcanics and tuffaceous sandstone ranging up to about 10,000 feet in thickness. Jurassic lacustrine shales, siltstone, micaceous sandstone and coal perhaps 1,500 feet thick underlie the Cretaceous. Triassic lacustrine sandy shale, sandstone and conglomerate about 4,500 feet thick dip under the Jurassic and rest on about 2,000 feet of Permian sandstone, conglomerate, carbonaceous shale and limestone, with basic volcanics.

The sediments are strongly folded and the Permian sediments on the west flank of the basin are intruded by auriferous quartz reefs.

Great Artesian Basin: Cretaceous lacustrine lignitic shales and sandstone up to 3,700 feet thick overlie marine shales, sandy shale, limestone and calcareous sandstone up to 4,500 feet thick. These overlie

Cretaceous lacustrine sandstone and shale up to 800 feet thick. The lacustrine sandstone and shale overlie the Jurassic sequence-about 3,000 feet of lacustrine sandstone, shale and coal seems. Over most of the basin the Jurassic rests unconformably on Palaeozoic or Precambrian rocks. On the northeastern edge the Jurassic rests on Triassic lacustrine sandstone and shale about 1,000 to 3,000 feet thick. This rests unconformably on Permian paralic shale and glacial sediments or on granite.

The Artesian Basin is a shallow structural basin with several basement ridges dividing the major basin into several smaller basins, including the marginal "offshoot basins." Most of the structural relief is probably produced by deposition over preexisting hills either in the basement or on surface of unconformity. There may be some tectonic folding on the eastern margin.

The Carpentaria Basin is the northern offshoot of the Great Artesian Basin. Marine Cretaceous sediments crop out around the south and east sides of the Gulf of Carpentaria. Between 2,000 and 3,000 feet of sediments overlying Precambrian basement have been proved by drilling near the south coast of the Gulf. The sedimentary Basin probably includes much of the area of the Gulf. Geological and geophysical investigation of this basin, including the Gulf, is being carried out by exploration companies at present.

Minor Basins: Only one of the minor basins is being explored —the Pirie-Torrens basin in South Australia. There, about 700 feet of Tertiary sandstone and siltstone with lignite unconformably overlie possibly Cambrian dolomite. Small oil showings have been reported from the Tertiary and? Cambrian.

EXPLORATION DRILLING DURING PERIOD 1946 TO 1955

State	No. of Bores	Total Footage	Systems Drilled
West. Aust.	22	110,000	Tertiary Cretaceous Permian Carboniferous
South Aust.	5	6,000	Tertiary Cretaceous Jurassic
Victoria	2	10,738	Tertiary
New South Wales	2	9,938	Jurassic Triassic Permian
Queensland	21	100,000	Cretaceous Jurassic Triassic Permian

PETROLEUM EXPLORATION VOLUMEN DURING PERIOD 1946 TO 1955

GEOLOGICAL AND GEOPHYSICAL PARTY-MONTHS

State	46	47	48	49	50	51	52	53	54	55	Total	
W.A.												
Geol.	4	4	7	15	20	15	20	30	46	44	205	
Geoph.	—	—	—	—	3	10	15	30	40	55		153
S.A.												
Geol.	—	—	—	6	6	6	—	—	10	10	38	
Geoph.	6	10	—	7	5	—	—	—	—	—		28
Vict.												
Geol.	—	—	—	6	6	6	—	—	2	7	27	
Geoph.	—	—	—	5	5	5	6	6	10	10		47
N.S.W.												
Geol.	—	—	—	—	—	—	—	—	20	10	30	
Geoph	—	—	—	—	—	—	—	—	12	14		26
Qld.												
Geol.	5	10	10	10	—	—	—	—	10	5	50	
Geoph.	5	10	10		—	—	—	—	25	12		62
								Total Geol:			355	
									Geoph:			316

NOTE: Work done in Northern Territory near the borders of W. A. and Old, is included in those states.

OIL AND GAS PROSPECTS

Although sufficient exploration work has not generally been done reliably to assess the prospects of the various basins, the present assessment may be summarized as follows:

Bonaparte Gulf Basin: Marine Palaeozoic sediments and anticlinal and fault structures are known, so this basin must be given a slight prospect of oil or gas accumulation.

Fitzroy Basin: Sequence known only in near littoral facies. Thick marine Palaeozoic sediments with anticlinal structure. Source beds known only in the Ordovician; reservoir beds not established. Moderate prospect of accumulation of commercial importance.

Canning Basin: Mesozoic and Permian marine sequence known; older Palaeozoic sediments in basinal facies possible; structures known. Moderate prospect of commercial accumulation but no definite stratigraphic targets.

Carnarvon Basin: Best-known sequence —Tertiary to? Ordovician marine sediments including several source-bed formations and a few sand reservoir formations; anticlinal structure known in Tertiary-Mesozoic but less certain in Palaeozoic. One oil well with good test flow. Prospect of commercial accumulations reasonably good.

Perth Basin: Sequence of marine and fresh-water sediments from Eocene, to Ordovician; some anticlinal structure indicated by seismic surveys. Slight prospect of oil accumulation exploration is justified.

Eucla Basin: Thin marine Tertiary to Permian sequence; no structures established. Very slight prospect of commercial accumulation.

Murray Basin: (South-west): Marine and fresh-water Tertiary-Mesozoic sediments; anticlinal and fault structures known. Prospects slight.

(North-east): Very little known. Thin Tertiary sediments over Permian fresh-water and marine sediments; some possibility of lower Palaeozoic shelf-edge. *Slight immediate prospects but warrants exploration.*

Gippsland Basin: No source rocks known in Tertiary sequence but possibility of drainage from down-dip; anticlinal structures found by geophysical surveys; present prospects slight but warrants continued exploration.

Sydney Basin: Few source beds or reservoir beds known in the Triassic-Permian sequence. Some prospect of gas but little prospect of commercial oil accumulation. Exploration justified.

Ipswich Clarence Basin: No source beds known. Some prospect of gas accumulation.

Maryborough Basin: Marine and fresh-water sediments Cretaceous to Permian, strongly folded. Sequence not well known. Some prospect, particularly on the easternmost structures. Exploration justified.

Great Artesian Basin: Stratigraphy, structure and palaeo-geography inadequately known. Many small oil and gas showings in water and oil bores. Fresh-water and marine sediments Cretaceous to Permian (plus Cambrian in west). Anticlinal structures known. Warrants much more exploration, although at present its prospects must be considered slight.

ACKNOWLEDGMENTS

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APPENDIX I

PETROLEUM AND GAS EXPLORATION IN SOUTH AUSTRALIA BY GEOLOGICAL SURVEY OF SOUTH AUSTRALIA

During the postwar years, exploration for oil and gas in South Australia has been confined mainly to the major sedimentary basins. They are the Great Artesian Basin, of which some 120,000 square miles lie in the northeastern part of the State; the Eucla Basin underlying the Nullarbor plain in the far west of the State and extending into Western Australia; and the Murray Basin which covers the greater part of the southeastern area of the State. In recent months exploration has also extended to the northern part of the Pirie-Torrens basin, lying to the west of the Flinders Ranges north of Port Augusta.

Great Artesian Basin: The Great Artesian Basin consists essentially of Mesozoic rocks overlain by variable, but generally thin, formations of Tertiary to Recent deposits. Basement rocks, where known, range from lower Palaeozoic to Precambrian in age.

The Mesozoic succession is incompletely known, in that few artesian bores have penetrated the full sequence to bedrock. The succession comprises the Winton formation (Upper Cretaceous) a fresh water series consisting of shales, sandstones and gravels, overlying the Rolling Downs formation (Lower Cretaceous). This is a marine series consisting of shales and mudstones, in part calcareous. The Walloon (Jurassic) formation is the main aquifer of the basin, and consists of soft sandstones, with some gravels and sandy shales, plant remains and lignite. Most known gas flows originate in these beds, which include the main aquifers of the basin.

No Triassic formations are known, but they may exist in the deeper, unexplored portions of the basin.

The structure of the basin is known only from bore information and from geophysical interpretation, since little information is available from surface mapping, owing to paucity of outcrops. Extensive recon-

naissance geophysical surveys, both magnetic and gravimetric, were made by the Frome Broken Hill Company in 1946 to 1948, over the Frome Embayment area, extending northwards into the southwestern part of the basin proper.

Geophysical interpretation, later confirmed by boring, showed that in the Frome Embayment there was little likelihood that the area contained structural traps with sufficient cover favourable to the accumulation of gas or oil.

Of the basin area north of the Embayment, bore hole data indicated only gentle folding in the sedimentary section, with structural relief influenced more by topography of underlying formations than by subsequent folding. Geophysical interpretation showed that, with the exception of two probable basement depressions in the order of 9,000 feet deep, the basin sediments were comparatively shallow. In general, the known stratigraphical section was deficient in likely source rocks for petroleum.

Eucla Basin: The Tertiary rocks of the Eucla Basin comprise fossiliferous limestone attaining a thickness of some 300-500 feet, underlain by up to 300 feet of Mesozoic sediments on top of chocolate shales and sandstones of undetermined age, but considered Lower Palaeozoic or Proterozoic. The thickness of the chocolate series in unknown, but exceeds 600 feet in places. Crystalline basement rocks underlie a large part of the basin, and appear to represent an ancient peneplaned surface. The Tertiary limestones dip gently toward the Southern Ocean. Reconnaissance geological and geophysical surveys failed to find evidence of suitable folded structures, or of thickening of the sedimentary basin northwards from the coast. There are no cover rocks above the limestone.

Murray Basin: The Murray Basin comprises Tertiary sediments, occupying approximately the former Murravian Gulf, and covering an area of 28,000 square miles in the southeast part of the State. The geological history of the basin is fairly complex and is best known in the Gambier Sunklands where the Tertiary formations attain their greatest known thickness. In the Murray valley area to the north, bedrock is known to be comparatively shallow, though near Loxton probable bedrock was cut in a bore at a depth of 1,600 feet. Within the limits of the basin, there are no breaks in the continuity of the

Tertiary, except for an area of Pre-Cambrian outcrops west of Serviceton-Murray Bridge railway, indicating shallow bedrock in that part of the basin.

The stratigraphic succession is known largely through bores sunk for water, with several deeper oil exploration bores. Basement rocks are lower Palaeozoic or Pre-Cambrian, and ar very incompletely known. Mesozoic formations have been recorded in a bore at Robe (Jurassic) and at Comaum (Cretaceous) but they do not outcrop in the South Australian portion of the Basin. The Tertiary is represented by the Knight Group (Eocene and Palaeocene) consisting of clays, sands, conglomerates and lignites with thin marine horizons; and the Gambier Limestones (Oligocene). Quaternary formations form only a thin veneer on the older sediments. Volcanic activity in the Plio-Pleistocene produced a variety of basic lavas and ash accumulation in the Mount Gambier district. The geological structure of the south-east area is complicated by block faulting ranging from late Tertiary to Quaternary, which accompanied the formation of the Gambier Sunklands. Several of the faults are known largely from geophysical evidence.

Current work in the basic includes aeromagnetic surveys over two Oil Exploration Licence areas, but no results are yet available.

Pirie-Torrens Basin

The *Pirie-Torrens basin,* is an artesian slope flanking the western side of the Flinders Ranges. Recent geological and geophysical work tends to discount the presence of a fault along the Range. The basin consists of Tertiary sediments overlying the Tent Hill formation, which in turn overlies basement rocks. The stratigraphic position of the Tent Hill formation is at present in doubt, since it is thought that this may represent the westward extension of the Adelaide System (Proterozoic) of the Flinders Ranges. Aeromagnetic and seismic work has been done in order to define bedrock and structure more accurately, but results are not known.

Exploration Drilling

Exploration drilling during the postwar years has been confined to the Frome Embayment area of the Great Artesian Basin, and to the Pirie-Torrens basin.

Four wells, totalling 5498 feet, were drilled east of Lake Frome, by the Frome Broken Hill Company in 1949 and 1950. The first, Cootabarlow No. 2 well, was drilled to aid geophysical interpretation, basement rocks being reached at 1390 feet, a depth much less than had been anticipated from geophysical work. Subsequently three further bores were drilled, namely Tilcha to the north, and Lakeside No. 1 and Black Oak to the south. All bores obtained artesian water, together with varying quantities of gas consisting largely of methane and inert gases. The evidence of these four bores shows a progressive thinning of the stratigraphic succession southward, the Walloons being absent from the most southerthly bore (Black Oak bore) which reached basement at 450 feet.

Near Wilkatana station, some 26 miles north of Port Augusta, Santos Limited is drilling a shallow well to obtain stratigraphical information in the Pirie-Torrens basin. The bore was in Tertiary beds to 430 feet. Appreciable traces of light honey coloured parafin based crude oil were obtained from the artesian water below 230 feet. The origin of the oil has not yet been determined, but may possibly be related to lignites occurring between 300 and 400 feet. The bore is in progress.

No exploratory drilling has been done in the Murray Basin in the past ten years. Drilling in the Eucla Basin was not considered warranted. 30/11/55.

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APPENDIX II

THE GEOLOGICAL OCCURRENCE OF OIL AND GAS IN QUEENSLAND BY GEOLOGICAL SURVEY OF QUEENSLAND

1. *Geographical Distribution of Sedimentary Basins Possibly Oil Bearing.*

Sedimentary basins occupy more than two thirds of the area of the State. By far the largest is that portion of the Australian Great Artesian Basin lying within its boundaries. This dominating structural feature covers an area of some 430,000 sq. miles, extending from near Cape York in the north and widening southwards until it occupies almost the full width of the State. Geographically, it lies in general to the west of the Great Divide and is limited to the northwest by a massif of Pre-cambrian metamorphics. An extension into the southeastern corner of the State provides a link with an outlying coastal basin around Maryborough.

In the east-central part of the State, a pitching geosynclinal basin occupies an area some 350 miles in length, widening southwards and westwards to merge structurally with and form the basal beds of that section of the Great Artesian Basin.

2. *Geological Description of the Basins*

Bowen Basin. Following a Hercynian movement, the Bowen basin developed as a miogeosynclinal structure in which sedimentation continued from early Permo-Carboniferous into the Triassic. The earliest beds (Lower Bowen Formation) are in general a series of continental bedded volcanics. Succeeding them, non-marine sandstones with coal seams, overlain by marine rocks predominantly sandy, form the Middle Bowen. Thick Upper Bowen coal measures cover the latter and are in turn overlain by freshwater Triassic shales and sandstones.

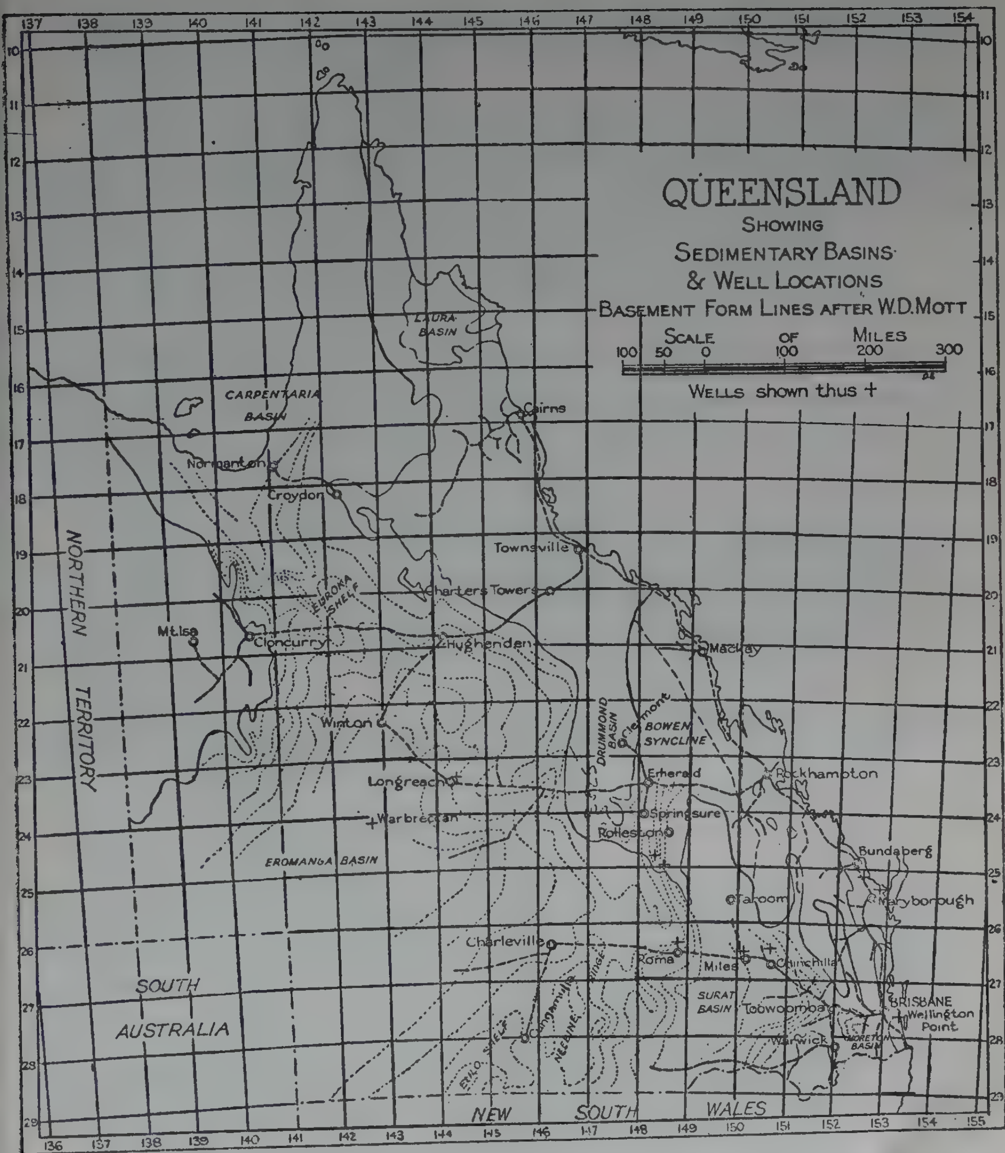
The Middle Bowen Formation, which constitutes the target for oil exploration, is characterised by marked facies changes. In the south-west, particularly, there is a progressive change westwards from marine facies within the geosyncline through a marine-paralic area to a predominantly continental sequence beyond the western limb where shelf sedimentation extends around the nose and northwards along the western flank of the basement anticline limiting the structure on that side. This change is accompanied by thickening of sedimentary sequence. In the Springsure district, the Permian is represented by a paralic to marine facies with maximum known thickness of 12,600 ft.

Sub-meridional folding is particularly well developed in the south-western section of the basin and structural closures have been developed. Five such structures have been tested by exploratory drilling and in one at least, lean petroliferous gas has been produced in quantity from Middle Bowen marine sediments.

Great Artesian Basin. Originating in Permian orogeny with the westward transgression of non-marine sediments, the basin developed by downwarping of the crust and concurrent deposition during the Mesozoic. Major development commenced in the Middle Triassic with a widespread transgression, during which the most important aquifer was laid down in the area south of the Euroka Shelf. Early in the Cretaceous, the limits of sedimentation were reached with extension northwards to form a basin centred on the Gulf of Carpentaria and allow marine invasion in stages of the Lower Cretaceous. Subsequent return to lacustrine conditions accompanied shrinkage of the area of deposition in Upper Cretaceous and Tertiary.

The basin as a whole is a composite structure due to the floor sagging irregularly on buried basement ridges, forming a number of sub-basins. The beds in general have a low southerly dip and attain a known total thickness exceeding 6000 ft.

Some 5000 water bores have been put down in the basin. Showings of inflammable gas and oil have been obtained in numbers of them in the eastern part of the basin, usually associated with artesian aquifers towards the base of the stratigraphic succession. In the Roma area, petroliferous gas in quantity occurs in a Triassic sandstone bed close to basement at approximately 4,000 ft., while to the east a very small production of oil has come from conglomerate immediately over-


QUEENSLAND
SHOWING
SEDIMENTARY BASINS
& WELL LOCATIONS
BASEMENT FORM LINES AFTER W.D.MOTT
SCALE OF MILES
100 50 0 100 200 300
WELLS shown thus +
LAURA BASIN
CARPENTARIA BASIN
Normanton
Croydon
Cairns
Townsville
Charters Towers
EUROKA SHELF
Mt Isa
Cloncurry
Hughenden
Mackay
Winton
DRUMMOND BASIN
Clermont
BOWEN SYNCLINE
Longreach
Emerald
Rockhampton
Warbreccan
Springsure
Rolleston
EROMANGA BASIN
Bundaberg
Taroom
Maryborough
Charleville
Roma
Miles
Chinchilla
SURAT BASIN
Toowoomba
BRISBANE
Wellington Point
Warwick
MORETON BASIN
NORTHERN TERRITORY
SOUTH AUSTRALIA
NEW SOUTH WALES

Company	Location	No. of Wells	Footage	Results
Wild Cat Rotary				
Associated Australian	Roma	3	11,152	Dry
X Oilfields N. L.		3	12,255	No. 4 proved as Gas well
Australiasian Oil X Exploration Ltd.	Rolleston	3	17,557	Dry
X Lucky Strike Drilling Co.	Maryborough	2	17,841	Dry
X Longreach Oil Ltd.	Longreach	4	13,059	Oil indications in No. 4
Shell (Q) Dev.	Rolleston	1	4634	Dry
X Westland Oil Co.	Warbreccan	3	16,711	Dry
X Winneills Pty. Ltd.	Wellington Pt.	1	3,950	Dry
		20	97,159	
Structure Drilling-Rotary				
Shell (Q) Dev.	Rolleston	61	41,000	
X Longreach Oil Ltd.	Longreach	7	2,736	
			43,736	
Percussion				
Condamine Oil Ltd.	Chinchilla	1	2,202	Suspended
Murilla Oil	Miles	1	—	
X Winneills Pty. Ltd.	S.E.Q.	15	3,500	Methane

lying granite. At Longreach and elsewhere wax occurs in Jurassic strata near granite bedrock. In the absence of pronounced folding, suitable reservoir conditions are sought on bedrock highs" or compaction folds in overlying porous beds.

Maryborough Basin. The Lower Mesozoic rocks of Southeast Queensland are succeeded in the Maryborough area by a thick development of continental volcanics possibly deposited in the early Cretaceous. These in turn are overlain by compact marine beds of Aptian age, followed by coal measures. The strata are strongly folded and appear to form the western part of a coastal basin now largely submerged.

3. *Exploration Drilling*

Extensive reconnaissance, detailed investigation of selected areas and scout drilling during the previous ten years led to the sinking of a dry well to 4634 ft., in the southern part of the Bowen Basin, 140 miles north of Roma in 1950-51.

In 1951-2, activity was confined to the sinking of three dry wells totalling 12,122½ ft. at Roma and percussion drilling in the Miles-Chinchilla district. During 1954, petroliferous gas was proved in quantity at Roma, but later attempts to prove reserves were unsuccessful.

Boom conditions in 1954-55 resulted in rotary drilling by six companies marked X in the following summary of drilling activities during the past ten years.

4. *Petroleum Exploration Volume*

In the years 1940-42 Shell (Q) Development, under prospecting titles, geologically investigated 250,000 sq. miles of country —12,600 sq. miles in detail, 200,000 sq. miles by geophysical surveys (largely gravimeter), 10,000 sq. miles by photomapping— and studied 3,280 water bores. During 1946-48 gravitational and magnetic surveys covered 2,500 sq. miles in the extreme southwest. The results of this work, together with departmental records and artesian water investigations, formed the basis for subsequent work.

In August 1955, 35 oil prospecting titles were held comprising 10 Petroleum Prospecting Permits and 25 Authorities to Prospect, covering in all approximately 385,700 sq. miles (more than half the size

of this state). Due largely to the paucity of outcrops in the Artesian Basin, normal geological methods are ineffective and approach is made by study of logs of water bores with limited reconnaissance. Normal geological methods apply elsewhere and more detailed work has been done around the Gulf of Carpentaria and eastwards, in the southern part of the Bowen syncline and in the Maryborough basin. Some 340,000 sq. miles in 20 areas has been covered thus by geological reconnaissance, aided where available by air photo interpretation. Of this some 15,000 sq. ml. has been mapped in some detail.

Gravity surveys have been conducted in four areas (Roma, Longreach, Warbreccan and Taroom) aggregating 13,500 sq. miles; seismic surveys at Comet and Roma (50 sq. miles) magnetometer surveys at Roma (4500 sq. miles) and Maryborough and aerial magnetometer reconnaissance surveys over the Gulf of Carpentaria (200,000 sq. miles) and semi-detailed work at Winton (11,600 sq. miles) and Tambo-Springsure (1,000 sq. miles).

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APPENDIX III

OIL AND GAS IN NEW SOUTH WALES BY GEOLOGICAL SURVEY OF N. S. W

1) *Geographical distribution of sedimentary basins possibly oil-bearing*
The basins which lie wholly or partly within N. S. W. are:

a) *Sydney basin* confined to east-central New South Wales.

b) *Clarence (or Ipswich-Clarence) basin* partly occupying far north coastal region of N. S. W. and extending northwards into Queensland.

c) *Great Artesian basin* partly present in northwestern N. S. W., the greater proportion of the basin being northward in Queensland and westward in South Australia.

d) *Murray River basin* party in southwestern N. S. W., extending southwards into Victoria and westwards into South Australia.

2) *Geological description of each basin*

a) *Sydney basin.* From the oil and gas prospect viewpoint, this is essentially a Permian basin of both marine and freshwater sediments, largely covered by Triassic freshwater beds. Thicknesses are variable with position in the structure. The Triassic rocks, dominantly sandstones and shales, have a thickness of up to 4,000 feet. The Permian succession is up to some 14,000 feet thick and contains several marine groups (Maitland and Dalwood Groups) and important Coal Measures (Newcastle, Tomago and Greta). The marine rocks consist chiefly of shales, sandstones, limestones, tuffs and conglomerates.

Several domes and anticlines, a monocline and some faulting are superimposed on the basin structure. There was some folding at the close of the Palaeozoic, some gentle folding at close of Cretaceous, and further folding in Tertiary times; and the Triassic is slightly uncon-

formable on the Permian in the northern part, but with angular conformity in the south.

Knowledge of the basement is incomplete. It is probably in part Devonian, in part Carboniferous.

b) *Ipswich-Clarence basin.* Jurassic freshwater beds form the greater part of the basin, and Triassic freshwater beds are known in parts of the structure, unconformably underlying the Jurassic rocks and with some pre-Jurassic tectonism. These freshwater series consist essentially of sandstones, shales, conglomerates and coal seams. Knowledge of thickness is incomplete; the Jurassic is at least some 3,500 feet thick and the Triassic a similar figure.

Underlying the basin unconformably are, for the most part metamorphosed pre-Permian (?) rocks, but in the northwestern sector some Permian marine beds outcrop and probably pass beneath the Jurassic cover. The basin is affected to some extent by Tertiary vulcanism and tectonic movements up to the Tertiary.

c) *Great Artesian basin.* Sequence and lithology of the basin in general is described elsewhere (Qld. and S. A.). In northwestern New South Wales, beds of the basin include Tertiary, Cretaceous and Jurassic sequences, but total thickness probably does not exceed 2,000 to 4,000 feet. The Cretaceous beds are essentially marine, chiefly shales, which are in part sandy, and sandstones which are in part calcareous. The Jurassic beds are chiefly of freshwater origin.

The basement rocks are Pre-cambrian in the far west, with also Palaeozoic rocks further east. Some anticlinal noses extend basinwards off the buried basement ridges. Some faulting (up to Late Tertiary) intersects the basin rocks.

d) *Murray River basin.* The basin is dominantly of Tertiary marine rocks, of considerable thickness, particularly in extensions southwards (but N. S. W. section probably does not exceed 2,000 ft.). The beds are probably mainly sandy at depth. Knowledge is mainly restricted to borehole data and geophysical interpretations.

3) *Exploration drilling during the last ten years*

a) *Sydney basin.* In 1955, Australian Oil and Gas Corporation Ltd. commenced the Kurrajong Heights No. 1 well, 42 miles north-west

of Sydney. The bore was to test for gas and oil on a structurally high part of a monocline with associated faulting. After passing through 2,876 feet of Triassic rocks the bore then penetrated Permian Upper Coal Measures and had entered Permian Upper Marine rocks when rotary mud-drilling was temporarily stopped at 4,755 feet. It is intended to proceed with percussive methods. A second percussive bore is proposed in the meantime on the Dural structure further east.

b) *Ipswich-Clarence basin.* In 1955, Clarence River Basin Oil Exploration Co. sank a bore by rotary mud-drilling at Grafton, discontinuing the hole at 4,583 feet. The bore is adjacent to an older bore which was sunk to 3,698 feet and from which samples of gas have yielded 15 to 18 per cent. ethane. Strata penetrated were essentially freshwater sandstones, shales and conglomerates.

4) *Petroleum exploration volumen*

a) *Sydney basin.* Australian Oil and Gas Corporation Ltd., from 1954 to present, has carried out detailed geological investigations, earlier mapping in the basin having also been conducted by the Geological Survey of New South Wales and University workers. Geophysical exploration by the above company has included extensive gravimetric surveys over 1,000 square miles, aeromagnetic surveys over 11,000 square miles, and some experimental seismic work.

b) *Ipswich-Clarence basin.* Some geological reconnaissance mapping by the Geological Survey of New South Wales and by private companies has been carried out. Australian Oil and Gas Corporation has covered 5,000 square miles by aeromagnetic survey.

c) *Great Artesian Basin.* In the period 1945-48, a subsidiary company of Zinc Corporation Ltd. conducted geological and geophysical surveys in the search for gas in the Frome Embayment section of the basin, which lies partly in N. S. W. The Bureau of Mineral Resources also carried out some geophysical work in this area. Some 15,000 square miles were covered by gravity and magnetic reconnaissance surveys.

d) *Murray River basin.* Gravity surveys by the Bureau of Mineral Resources.

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AUSTRALIA

OIL SEARCH IN VICTORIA

By N. Boutakoff, D. Sc. [1]

ABSTRACT

In Victoria, oil was first discovered in 1924. Subsequently, over a period of some fifteen years, very small production was obtained from many shallow wells in the Lakes Entrance area of East Gippsland. Attemps to win oil by horizontal drilling from a chamber situated at the bottom of a shaft, were pursued until late 1951, but proved a commercial failure and the works were closed down at the end of that year.

Renewed interest in oil exploration in 1954, switched attention from East to West Gippsland, an area which had not previously been explored. Drilling was preceded by considerable magnetometer, gravimetric and seismic exploratory work. In addition to the Tertiary sediments of the Gippsland Basin which had hitherto produced all known oil, attention is now focussed on deeply buried Mesozoic, Carboniferous and Devonian rocks.

As this paper is being written, oil has for the first time been discovered in two wells of south-west Gippsland.

Significant though this recent discovery is, it is still too early to evaluate its full potentialities.

Oil search is also being extended to all other sedimentary basins of the State in which, however, previous drilling failed to reveal any trace of petroleum.

1. THE HISTORY AND THE GEOGRAPHICAL DISTRIBUTION OF OIL PROVINCES

All oil at present known in the State of Victoria is contained in rocks of the Gippsland Sedimentary Basin. Among the six Sovereign States of the Commonwealth of Australia, Victoria is the southermost continental State and it is in the south-eastern corner of this territory, in other words in the extreme south-eastern corner of the Australian Continent, that the Gippsland Sedimentary Basin is located. It is, more-

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over, in the eastern corner of that Basin that oil was first discovered in 1924. Some forty wells were sunk around Lakes Entrance, a locality of East Gippsland, over a territory of about eight square miles; and this small territory produced all the oil of the State until late 1951, when production came to a standstill.

As a result, in part, of suggestions contained in a paper published by the writer in 1951 (Boutakoff, 1951, pp. 56-57), attention was then directed to south-west Gippsland and considerable preliminary geophysical work was carried out in that area in the years 1951-1954. By that time, interest in oil exploration was renewed by the discovery of oil at the diagonally opposite corner of the Australian Continent, near Exmouth Gulf. As a result of this renewed interest, three deep wells were sunk: first the Frome-Lakes Company well on the Darriman structure (4,610 feet) which proved dry: then the Woodside (Lakes Entrance) wells No. 1 (6,008 feet) and No. 2, at present drilling at 4,180 feet, both of which struck significant showing of oil. These wells, located "south of the Won-Wron monocline, between that structural feature and the coast", have confirmed the writer's opinion, expressed in 1951, that in that area "other reservoir and/or accumulations of oil may occur" (Boutakoff, 1951, pp. 57). However, it is yet too early to assess whether oil is present there in commercial quantity.

At present, therefore (see map, figure 2 and sections, figure 3), oil is known to be present at both ends of the Gippsland Sedimentary Basin, north-east at Lakes Entrance and south-west at Woodside Dunes. Between these borderline provinces, considerable boring in the central part of the Tertiary Basin (Section No. 2) has failed to reveal the slightest trace of oil.

In 1954, the writer of the present paper suggested that this peculiar oil distribution may be the result of migration from deeper sources, a point of view which will be discussed in some detail at a later stage in the present paper. This new approach to Gippsland petroleum geology has also been discussed in a recent paper (Boutakoff, 1954-1955). As a result of this publication, considerable interest is now directed to some older rocks, underlying the Tertiary sediments of the Gippsland Basin and including the Mesozoic, Carboniferous and the Upper and Middle Devonian. There is some evidence at hand to show that residual oil is to be found in the above-mentioned Palaeozoic rocks, cropping out around the rim of the sedimentary basin.

In Eastern Gippsland, as section No. 2, figure 3 shows, Tertiary oil-bearing sediments directly overlap granitic and metamorphic rocks and this oil province is therefore limited in scope to Tertiary possibilities. On the other hand, as it will be apparent from both sections of figure 3, the western oil province of Gippsland offers considerable scope in formations older than Tertiary and these possibilities indeed extend to Central Gippsland, below the barren Tertiary sediments of that area. So that the possibility now exists of a third petroliferous province soon appearing on the scene in Central Gippsland. An encouraging pointer in that direction has been the recent petroleum show at 4,430 feet, in Mesozoic (presumably Jurassic) coarse sandstone in Woodside well No. 1.

2. STRATIGRAPHY AND STRUCTURE

A) *Stratigraphy*. From the oil winning standpoint, the "basement" of the Gippsland Sedimentary Basin is made up of Cambrian, Ordovician and Silurian rocks which are all, to some extent, penetrated by granitic and other plutonic intrusions and have consequently undergone some considerable degree of metamorphism and mineralization. Moreover, these rocks are intensely folded and faulted. The rocks which present some interest from the point of view of oil exploration, begin with the Middle Devonian and extend to the base of the Pliocene.

a) *Middle Devonian*. The Middle Devonian is made up of reef limestone showing traces of residual oil in outcrop, which is associated with other highly fossiliferous sediments. These reefs are now cavernous and some of these caverns may date back to the unconformity by which *terrestrial* Upper Devonian sediments rest upon the Middle Devonian reefs. This possibility renders the Buchan reef limestones interesting from the point of view of oil exploration. Downward, these reefs pass into the Snowy River porphyries.

Paleogeographic conditions appear to have been considerably different east and west of the Mt. Wellington Belt (figure 1). West of that belt, there is apparent conformity of deposition from the lower Ordovician to the Lower Devonian inclusively, so that neither the Benambra nor the Bowning Orogenies, *as defined by David and Brown* [2]

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[2] "The Geology of the Commonwealth of Australia", Vol., 3 Edward Arnold & Co. London, 1950.

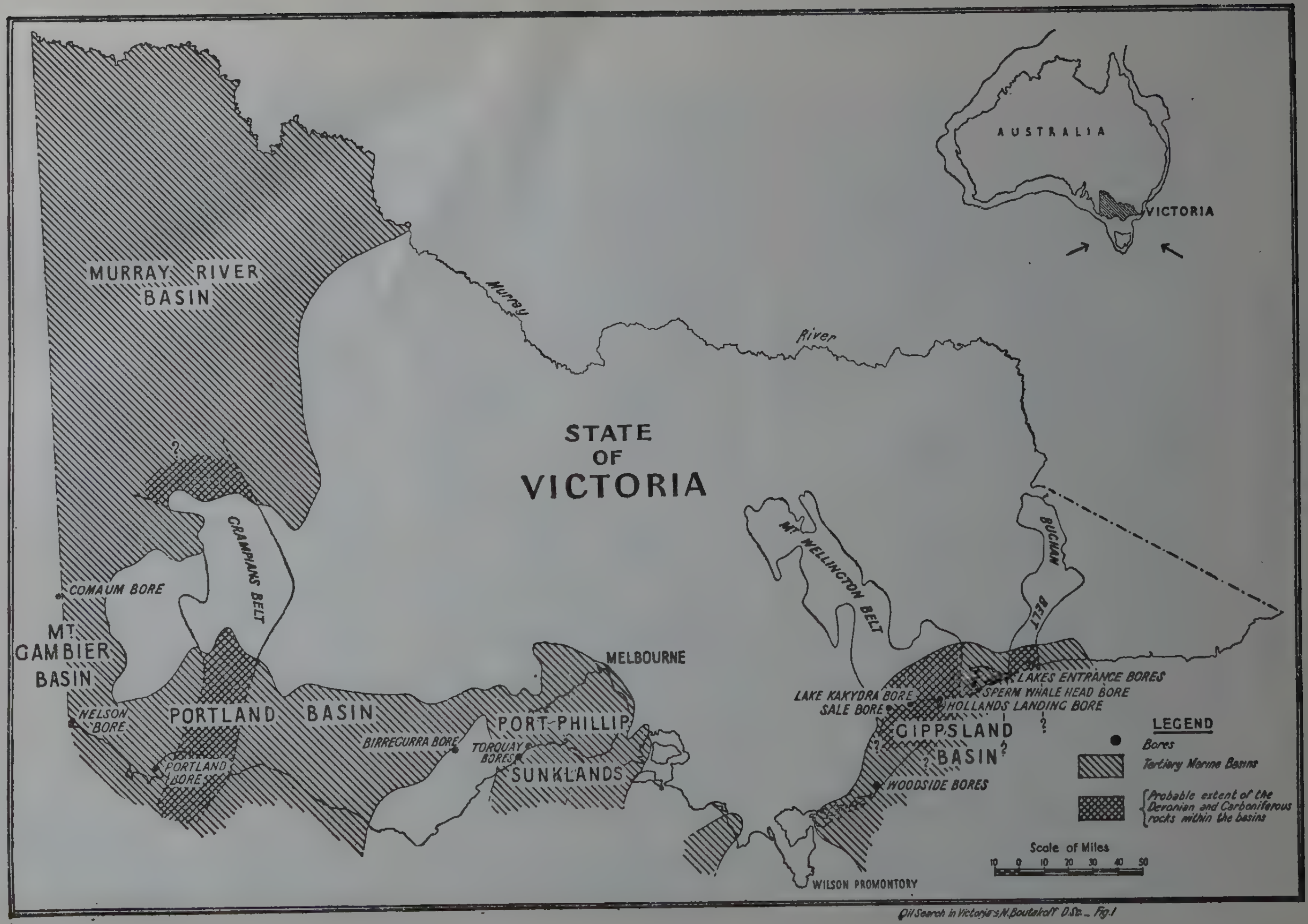

Fig. 1—The Tertiary Sedimentary Basins of Victoria.

appear to have occurred here. East of the Mt. Wellington Belt, however, the Snowy River Porphyries rest unconformably upon the Upper Ordovician. These porphyries are Middle Devonian according to some, but Lower Devonian according to others.

b) *Upper Devonian and Lower Carboniferous.* The Upper Devonian is unconformable over the Middle Devonian, but forms a unit with the overlying and conformable Lower Carboniferous. Contrary to the sharper folding of the Middle Devonian and older sediments, the Upper Devonian-Lower Carboniferous series are gently folded in a series of rolling anticlines and synclines. They form a belt which crosses the northern edge of the Tertiary basin from N. W. to S. E. but which, within the basin, probably swings over to a N. E.-S. W. direction. The thickness of these beds is considerable, running into 5,000 or more feet. Some of these beds are undoubtedly terrestrial or fresh water deposits, but marine intercalations are by no means excluded. Good porous and permeable sandstones alternate with mudstones and shale and offer considerable reservoir rock possibilities. Lavas are also included among these rocks.

c) *Jurassic and possibly Cretaceous.* A considerable gap separates the base of the Jurassic sediments from the top of the Carboniferous beds. At the close of the Lower Carboniferous times occurred the folding to which is attributable the deformation of the Upper Devonian and Lower Carboniferous rocks. Moreover, the Palaeozoic Ice Age set in after this period of diastrophism and continued well into the Permian. Permo-Carboniferous glacial sediments have almost been swept away from Victoria and are preserved only in more or less isolated patches, mostly in and around sedimentary basins and also elsewhere, in downfaulted troughs. Triassic remnants are even less common, so that it becomes apparent that a very considerable period of denudation has preceded the deposition of the Jurassic sediments.

Jurassic deposition, running into some 3,000 or more feet, occurred in rapidly sinking basins. Since only plant remains have so far been found in these sediments, they have been described as fresh water throughout. Nevertheless, the possibility of the occurrence of marine or brackish intervals exists.

Jurassic sandstones are, generally speaking, poor reservoirs, with small porosity and permeability and with much fine silt clogging the pore space. However, here and there, some porous, permeable and

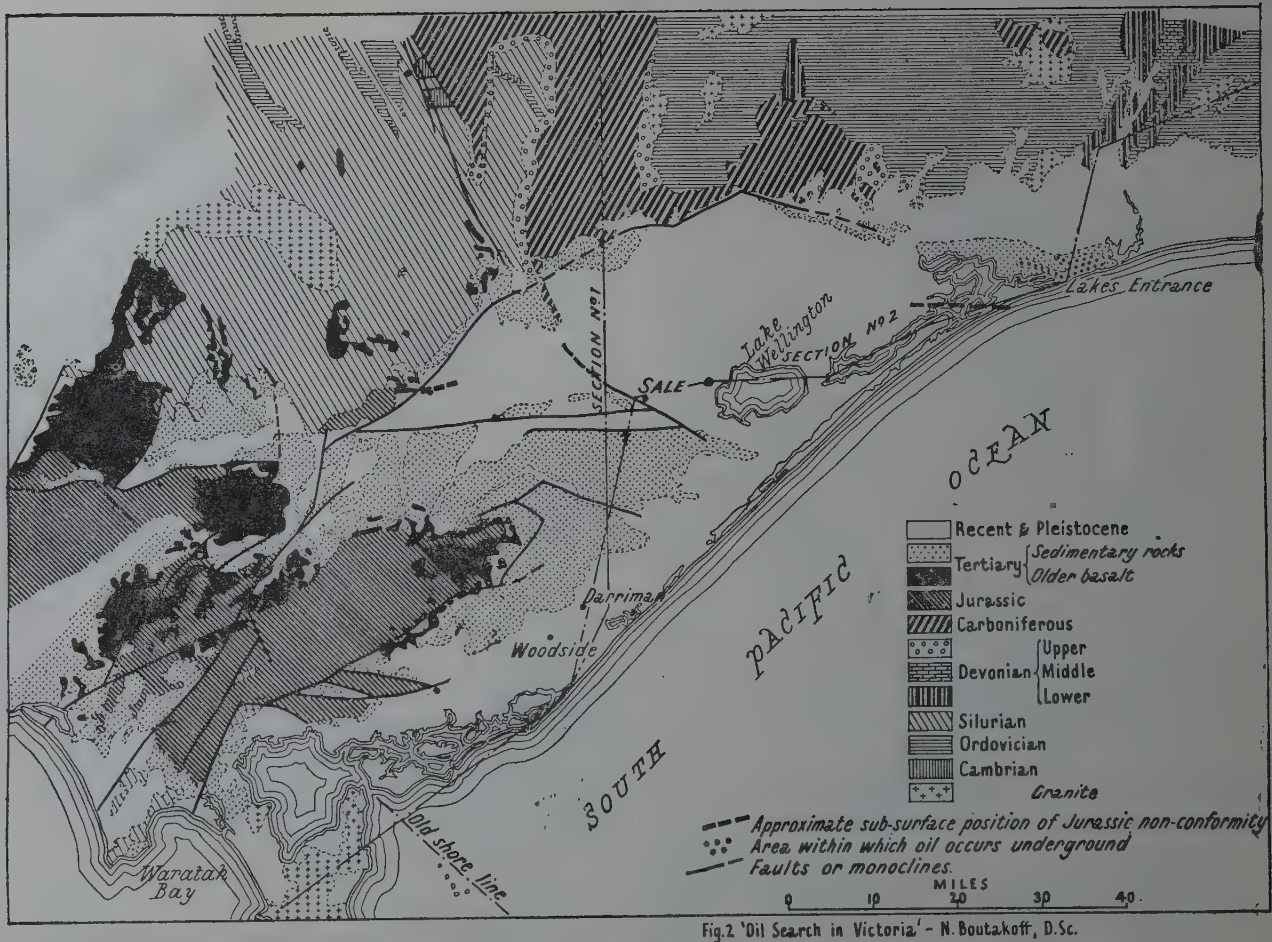

Fig. 2—Geological map of Gippsland, Victoria, showing position of sections.

coarse arkosic sandstones do occur and these may, in favourable circumstances, contain some oil. Cretaceous sediments are so far unknown in Gippsland. Since, however, Marine Cretaceous occurs in the Mt. Gambier Basin (Nelson Bore) similar occurrence in central coastal Gippsland is possible.

d) *Tertiary Sediments.* The Tertiary formations may be conveniently divided into a lower brackish and fresh water series, mainly composed of gravels and sands, with some clay intervals and also containing basalt and some very considerable brown coal deposits in the western part of the Gippsland Basin; and an upper marine series, largely composed of limestone and marl of polyzoal origin, but also containing some glauconitec sand at the base and passing laterally to more silty, sandy and gravelly facies, as the coastlines of the Tertiary seas are approached. It is in these basal and lateral shoreline facies sands that Tertiary oil accumulation so far known has taken place.

The basal, fresh water and brackish coal bearing series are attributable to the Eocene. The Upper Marine Series range from the Oligocene to the Lower Pliocene.

In Upper Pliocene and Pleistocene times, considerable piedmont gravel accumulation has taken place over most of the Gippsland Basin, forming a series of piedmont river fans, passing seaward into marine sediments.

The overall and individual thicknesses of the Tertiary beds undergo considerable variation from the centre to the edges of the sedimentary basin. At Hollands Landing (see fig. 3) about 4,000 feet of Tertiary sediments have been encountered in boring, but this thickness drops to less than 2,000 feet in Lakes Entrance and to some 2,500 feet in the Woodside area. On the other hand, as the sections in figure 3 show, the lower, coalbearing Tertiary increases in thickness from East to West, mainly on account of the enormous accumulation of brown coal deposits, some of the seams of which run anywhere from 1,000 to 260 feet in thickness (Darriman, Woodside and Baragwanath Uplift Bores).

e) *Concluding Stratigraphic Remarks.* Reference to the sections of figure 3, clearly brings out the fact of the existence in Gippsland of several major unconformities, dividing the accumulated sediments into a series of overlapping bodies. The overlapping wedge-shaped edges of these sedimentary units are, it is thought, a major factor in oil migration and distribution. This point will be discussed later in some detail.

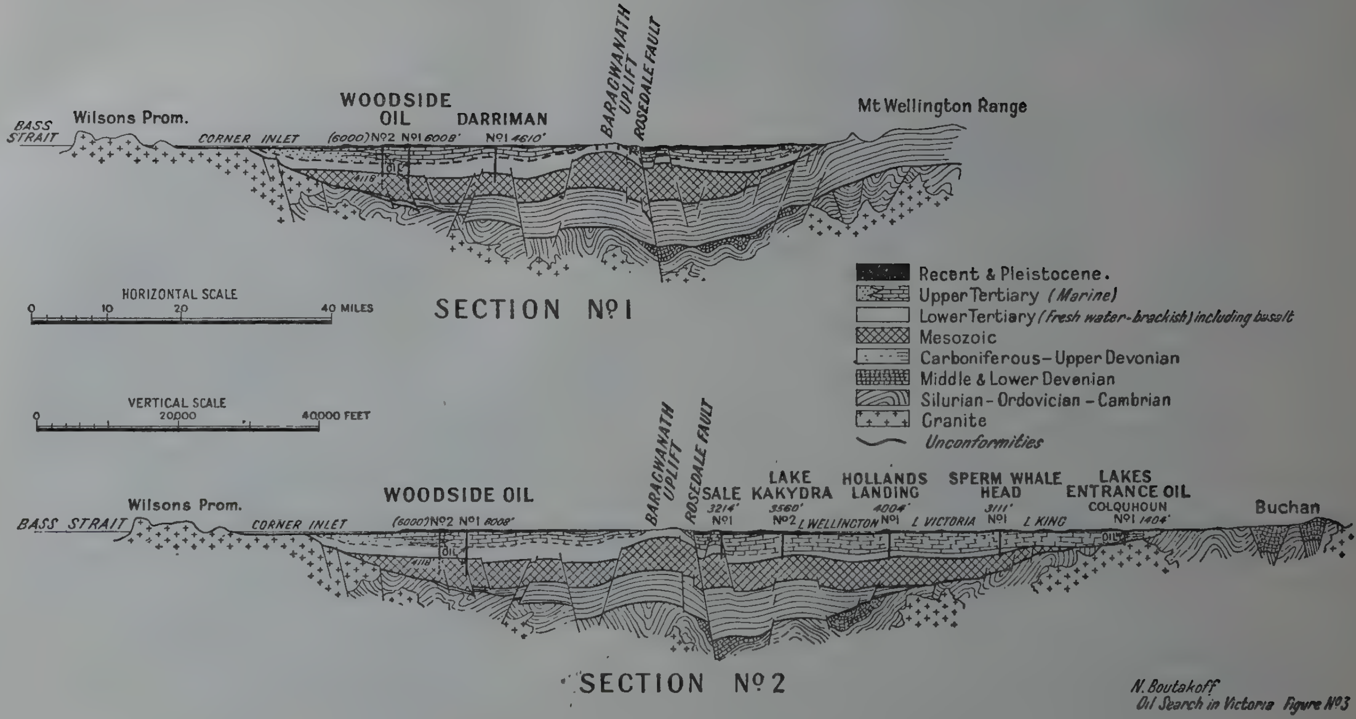

Fig. 3—Sections across the Gippsland Sedimentary Basin, Gippsland.

In addition to these known wedge-like sedimentary overlaps, there may exist still unknown wedges hidden at depth: Devonian and Carboniferous may become marine sediments at depth. Permian and Triassic *marine facies* wedges are a definite possibility offshore or along the coast. Marine Permian occurs in New South Wales and again in Tasmania, across the shallow Bass Strait from Gippsland. Similarly, Jurassic marine rocks may exist close at hand. As stated before, marine Cretaceous may be expected to occur in portions of the Gippsland Basin.

In considering these possibilities of changes from fresh water to brackish and marine environment and also the possibility of marine sediments so far unknown in outcrop, occurring at depth in the Gippsland Basin, the very position of the Gippsland Sunklands on the edge of the Continent must be kept in mind. A vast triangular Continental shelf exists off the coast of Gippsland. It was previously pointed out (Boutakoff, 1954-1955, p. 43) that this shelf is a part of the heritage of the geosynclinal conditions which have prevailed along the eastern coast of the Australian continental mass since early Palaeozoic times.

On the other hand, the continental pediment which still links Australia with Tasmania (Boutakoff, 1954-1955, p. 53, figure 1) has always been an area of deposition of land and fresh water sediments from as far back as the Middle Carboniferous until the advent of the Mio-Pliocene. The dividing line between these two areas, with so sharply differing histories behind them, can be taken as the rectilinear chain of granitic islands extending from Wilson's Promontory to Tasmania, through the Kent and Furneaux groups. From the continental mass to the west of this line, shoreline sediments in the shape of sands and grits, were fed into the Gippsland Basin. Likewise, from the oceanic environment to the east, marine wedges tended to overlap northward and westward, from the Lower Palaeozoic onward. It is only when the Tertiary sea broke across this continental pediment and was succeeded by the Pleistocene and modern Bass Strait, that the old palaeogeographic relationship was partly masked. It will be seen that, apart from explaining the reason why marine sediments may be expected at depth west of Wilson's Promontory and south of the Australian Alps, this very special position of the Gippsland Basin is also an excellent one, from the oil prospecting point of view. It sharply differentiates this basin from the other Tertiary sedimentary basins of Victoria, which are all strictly epi-continental, with the sole exception of the extreme south-

western edge of the Portland Basin. And there precisely, as I have mentioned previously, marine Cretaceous is found to lap over the edge of the old continental mass from the south-west: conditions on the eastern and western edges of the continental pediment must have been similar indeed. (Fig. 1, inset; arrows show marine overlaps).

B) STRUCTURE

a) *The Structural Plan.* The structural framework of Gippsland is somewhat complex. Palaeozoic orogenies have occurred here along N. E.-S. W. and N. W.-S. E. axes. On the other hand, Mesozoic and Cainozoic epirogenic movements, accompanied nevertheless by marked warping and even folding, occurred over E.N.E.-W.S.W. and W.N.W.-E.S.E. axes, approximately normal to the old Palaeozoic trends. To these latter movements, the Gippsland Basin owes its existence, together with the subsidiary structural features which complicate its framework.

b) *Basin Subsidence and Bounding Faults.* From Mount Wellington (fig. 3, sect. 2) where Carboniferous rocks are exposed at 5,268 feet, to the base of the Jurassic rocks under Lake Wellington, there is a drop of some 11,000 feet. This figure is based on the known thickness of Tertiary sediments (Lake Kakydra bore: 3,500 feet) and an estimated thickness for the Jurassic of some 2,500 feet. It may even be somewhat greater, should the Jurassic thickness extend to 3,000 feet. Details of faulting by which this considerable axial drop takes place, are not well known. It is known, however, that step faulting, considerably more complicated than shown on figures 2 and 3, occurs all along the northern edge of the basin.

c) *Axial Uplift.* From east to west, the Basin is divided in two by an axial uplift. This uplift is composed of the great Carrajung Jurassic structure (figure 2) nosing eastward along the long axis of the basin. Eastward, this structure is relayed en echélon by the Baragwanath Uplift, which extends up to the south-western shores of Lake Wellington (figure 3). Several subsidiary uplifts and downwarps complicate the picture and reference to figure 2 will show their position in relation to the main structural theme.

This great updoming subdivides the western portion of the Gippsland Basin into a northern and a southern, east and west directed,

trough. And it is in the extreme south-western corner of the southern trough, where the Jurassic uplift encounters the old palaeogeographic shoreline discussed above, that the recent oil finds have taken place.

d) *Subsurface Distribution of Devono-Carboniferous Rocks*

An all-important question from the standpoint of deeper petroleum exploration in Gippsland, is the distribution and structure of Devono-Carboniferous rocks buried below the Jurassic unconformity. As pointed out previously, there are reasons to believe that, upon entering the basin, the N.W.-S.E. belt swings over to the south-west. This is because all tectonic trends, in Eastern Victoria, undergo this change of direction. For instance, the Silurian rocks north of the western part of the basin are directed N.W.-S.E. but in the elongated outcrop north of Waratah Bay and along the shores of that bay to Cape Liptrap, they are directed N.E.-S.W., (Thomas, 1939). Since, moreover, lowermost Devonian is present alongside the Silurian rocks at Waratah Bay, the possibility exists that this Lower Devonian represents the western border of the Mt. Wellington Devono-Carboniferous belt. Should this be true, Devono-Carboniferous rocks may be present below the Jurassic rocks of Darriman and Woodside.

Structural conditions of these rocks buried below two (and, in the case of Middle Devonian, *three)* unconformities are of course quite unknown. In any detailed work, projection into the basin of structures existing to the north is, at best, a very unsatisfactory procedure, although gravity work in the Gippsland Basin indicates that broader tectonic features do enter the basin and do extend for some distance within it (Dooley 1952; Dooley and Mulder 1953; Boutakoff 1954-1955, pages 52-53, Plate I). It may perhaps be possible to solve this difficult problem by seismic refraction methods.

More detailed discussions of problems of stratigraphy and structure may be found in a recent paper devoted to the petroleum geology of Gippsland (Boutakoff, 1954-1955, pp. 39-49).

3. OIL MIGRATION AS RELATED TO STRATIGRAPHY AND STRUTURE

As it occurs in the Tertiary rocks of Lakes Entrance, Gippsland oil is a most peculiar fluid. It contains no gasoline and kerosene fractions and intead of ethane, methane alone is associated with it. Moreover,

no salt water is found with this oil, whereas artesian fresh water underlies it.

It is difficult to escape the conclusion that this is a depleted oil and that it is closely associated with the *unconformity* by which Tertiary beds overlap older geological formations. From work carried out in horizontal drilling from the bottom of the Lakes Entrances shaft over a period of some ten years, it appears that much of the oil occurs as a scum over artesian water filling the basal Tertiary gravels; from this scum some oil has also migrated into overlying glauconitic sandstones. Since the Tertiary sediments have so well sealed the oil that no seepages occur even at the unconformity outcrop, it must be assumed that exposure and depletion of the oil occurred *before* it was again buried by the Tertiary sediments.

In Woodside bores No. 1 and No. 2, at the other extremity of the Gippsland Basin, conditions are quite similar, except that no artesian water is there associated with the oil. These wells, however, have provided cores of the contact of the marine Oligocene marls and sands, with the Eocene coal beds. The coal appears to be deeply cracked as it would be in exposed beach outcrops and the marine marl penetrates each crack. There is evidence, therefore, that prolonged exposure and desiccation of the Eocene coal-bearing sediments occurred before their burial by the Oligocene marine deposits and during this exposure, Gippsland oil may have seeped and become depleted.

The problem of the origin of this oil and of the location of its original reservoir may be solved on the basis of the following observation:

The only bores to contain oil in East Gippsland are those in which Tertiary strata directly overlap granite or metamorphic rocks injected by granite. As soon as Mesozoic rocks are encountered below the Tertiary unconformity, there is no oil in the Tertiary beds, nor at the unconformity, although the composition of the overlapping Tertiary strata has undergone no change. This observation points to the importance of the Mesozoic formations as a sealing blanket.

Now, the Mesozoic blanket rests unconformably over Palaeozoic rocks, forming an overlapping wedge which is itself overlapped by the Tertiary sediments. Both sedimentary blankets dip oceanwise and the Tertiary mantle front, extending farther inland than the Mesozoic wedge, comes to rest directly over the Palaeozoic rocks, in front of the buried Mesozoic wedge (figure 3, section No. 2).

Any oil migrating from under the Mesozoic wedge will find its way into the overlapping Tertiary sediments, where it is trapped. Since oil can only migrate up-dip the oil accumulation will be restricted to that part of the Tertiary sediments which extend above and *beyond* the Mesozoic edge from which the oil is proceeding. And this precisely is what drilling shows to be a fact in East Gippsland, where the Jurassic cover has been largely left undisturbed.

In West Gippsland, at Woodside, the Jurassic edge is highly fractured, as shown by cores in Woodside No. 1 well. Some oil therefore, is found a short distance away and basinward from the edge of the Jurassic wedge underlying the Tertiary reservoir. Moreover, the occurrence of oil at 4,430 feet within fractured Jurassic rocks, clearly confirms the reasoning developed above.

It is, therefore, suggested that the original oil reservoirs are situated somewhere under or, perhaps, within the Mesozoic sedimentary wedge and that drilling should be deepened to reach through the Mesozoic blanket into the Palaeozoic sediments below. Until this is done, it cannot be said that the Gippsland Basin has been at all adequately explored.

It will be seen that this approach explains the position of oil accumulations around the rim of the basin, so strikingly depicted by section No. 2 in figure 3.

A contributing factor of great importance is also provided by the change in facies which the calcareous sediments of the Gippsland Basin undergo, as they approach the old Tertiary shorelines. Facies explains the lack of accumulation of oil on the faulted Baragwanath and similar subsidiary uplifts, such as the Darriman Structure. These uplifts have disturbed the deeper, calcareous parts of the basin, where sands suitable for oil accumulation do not exist and where permeability and porosity are notably poor. These structures have consequently failed to attract any oil.

It would seem that in Gippsland, facies is the key to oil accumulation in the Tertiary sediments and that such accumulation may only occur near the Basin margins. Conversely, structural features are of prime importance where older (Palaeozoic and Mesozoic) rocks are concerned and if any petroleum occurs in these rocks, it is likely to be accumulated over more centrally located uplifts, within the basin. It appears, however, that the problem is complex and that several different types of oil may be present in Gippsland.

Considerations of facies however, cannot be invoked as an argument against oil migration from deeper sources: the sands which contain oil at Lakes Entrance, extend unchanged as far west as Lake Wellington; yet all traces of oil vanish in them, as soon as Jurassic rocks appear below them.

4. EXPLORATION IN OTHER SEDIMENTARY BASINS OF VICTORIA

Some drilling has been carried out in the other Tertiary sedimentary basins of Victoria and a few deep holes have been sunk in them (figure 1). No trace of oil, however, has been discovered so far. As explained above, only the Portland Basin, where it coalesces with the Mt. Gambier Sunklands of South Australia, can be compared with Gippsland, being situated on the edge of the Australian continental mass. The other basins and most of the eastern half of the Portland Basin, contain only epicontinental and relatively thin marine deposits.

1. *Nelson and Portland Bores.* In 1894 at Portland, a bore was sunk for brown coal, but encountered marine Tertiary down to 2,265 feet, without reaching its bottom. At Nelson, a well was sunk for oil in 1946 and reached 7,305 feet. This well is interesting in that it encountered below 4,500 feet *marine* Cretaceous sediments which are evidently overlapping the Australian-Tasmanian continental pediment from the south-west. Above these marine Cretaceous sediments, brackish Eocene and Paleocene sediments extend up to 992 feet. These, in turn, support the Oligocene and Miocene marine marl and limestone beds equivalent to those of Gippsland. Considerable developments of coarse, porous and permeable sandstones and sand have been encountered in this bore below 4,500 feet. It may be stated that, from the oil exploration point of view, there is here too much sand and insufficient cover. No oil has been encountered in either bore. (Boutakoff and Sprigg 1953; Baker and Cookson 1955, where further references will be found).

2. *Comaum Bores.* Two bores near Comaum on the South Australian border, one sunk in 1926 (1,171 feet) and the other in 1953 (708 feet) are interesting, because from the latter bore Cookson (1953a) has again identified Cretaceous sediments, but this time, nonmarine. No trace of oil has been noted from either of these bores.

3. *Birregurra Bore.* This bore, sunk in 1953, reached a depth of 1,103 feet. Passage from the Upper Tertiary marine polyzoal marl and limestone series to the brackish and fresh water lower Tertiary occurs in this bore in the 690′-695′ interval. Mesozoic was entered at the depth of 1,063 feet and in the upper ten feet of the Mesozoic, Cookson has again identified non-marine Cretaceous, passing downward into Jurassic (Cookson, 1953 b).

3. *Sorrento and Torquay.* At Sorrento, about 25 miles east of Torquay, a bore reached 1,696 feet in lower Tertiary beds. Small brown coal and lignitic beds were encountered, but no oil. Torquay attracted much attention on account of the gentle folding into several dome-like structures, which the Tertiary sequence undergoes there. Some seven shallow bores were sunk in that area, the deeper ones penetrating the Jurassic at 823′, 886′ and 690′ respectively. The deepest bore reached 1,453 feet. The usual sequence of clay, limestone and glauconitic limestone Upper Tertiary marine beds, overlying lignitic and arenaceous lower Tertiary brackish to fresh water beds, was encountered. Traces of oil were claimed but never proved or confirmed and remotely measureable quantities of oil have not been available, in spite of excellent reservoir rock conditions and perfect structural closures.

4. ASSESSMENT OF POSSIBILITIES IN TERTIARY SEDIMENTARY BASINS OF VICTORIA, EXCLUDING GIPPSLAND

In evaluating the petroleum possibilities of the State of Victoria outside Gippsland, it is necessary to separate the south-western part of the Portland Basin area from the other basins. Excluding then the latter area, all other Tertiary sedimentary basins of Victoria have some common traits which render them poor prospects in the search for oil. All these basins are shallow and epi-continental. Although Mesozoic rocks largely underlie them, these rocks are in turn directly underlain by highly metamorphic and intensely folded sediments, ranging from the Cambrian to the Silurian, by granite and by other plutonic rocks. This circumstance cuts down petroleum possibilities to Mesozoic and Tertiary. Mesozoic sediments, as evidenced from the Comaum, Birregurra and Torquay bores, are entirely fresh water, both in respect to Cretaceous and Jurassic. No trace of oil is known to have been found in these rocks and it is difficult to see, considering that they rest on

mineralized metamorphic and igneous rocks, from what source oil can have reached them. The Tertiary sequence is shallow and has so far failed to evidence any authentic sign of oil. It appears, therefore, that in these epi-continental Tertiary basins, including most of the Victorian part of the Murray basin, the chances of finding oil are slim indeed. The Victorian section of the Murray Basin is well known through very numerous shallow water bores, many of which have reached its metamorphic basement. The Tertiary formations are there quite barren of oil. The western part of the Portland Basin stands apart in this evaluation. It contains wedge-like marine overlaps of Cretaceous and probably Jurassic rocks in the Nelson area, the Tertiary sequence is very thick and the Devono-Carboniferous Grampians sandstone belt underlies the deeper part of this basin. Possibilities analogous to Gippsland do appear to exist here and deep drilling is definitely warranted in the light of the most recent data on this area. It may be that the southernmost part of the Murray basin, where it adjoins on the South Australian border and is underlain by Devono-Carboniferous rocks, may also prove to be of some interest.

5. CONCLUSIONS

Oil search in Victoria has entered a new phase. A much broader outlook is evident among oil operators, and the deeper, non-Tertiary rocks buried in some of the sedimentary basins of this State, are drawing much attention in addition to Tertiary possibilities. In respect of these deeper oil possibilities, the Gippsland Basin comes first, with the south-western portion of the Portland Basin being possibly a hopeful second in this respect. Doubtful possibilities may also exist in respect of the older rocks in the south-western portion of the Murray Basin.

Tertiary possibilities in the writer's opinion are restricted to the Gippsland Basin and to the western part of the Portland Basin, although here no authentic traces of oil have hitherto been encountered. Nevertheless, it cannot be said that two bores, even be they deep bores, are sufficient evidence to disprove this area.

APPENDIX

1. *Boring Records.* One hundred and forty bores were sunk in Gippsland between the years 1924 and 1951. The position of these bores is shown in Boutakoff, 1951, p. 51, fig. 1, where they are recorded under a number and a Parish name. Data on bores so recorded are preserved in the Boring Records, Mines Department Victoria. Of these bores, 40 have been drilled in the immediate vicinity of Lakes Entrance and have either shown or produced some oil. The rest, situated outside this area, have recorded no oil.

Apart from bores, a shaft was sunk at Lakes Entrance in 1942 and horizontal drilling carried out from a chamber at the bottom of the shaft (1,117 feet) up to 1951.

In 1955-56, three deep bores were sunk in South-west Gippsland viz.: Darriman, Woodside No. 1 and Woodside No. 2, data respecting which are contained in the present paper.

2. *Production figures from Lakes Entrance, Gippsland*

		gallons			gallons
1930	—	10,000	1935	—	4,320
1931	—	20,000	1936	—	3,783
1932	—	20,000	1937	—	9,372
1933	—	20,000	1938	—	6,173
1934	—	5,588	1939	—	4,807

3. *Oil Characteristics*

1. LAKES ENTRANCE OIL

Gippsland (Lakes Entrance) oil characteristics are as follows: 15.7° A. P. I. gravity.—S. G. 0.961. It is an asphaltic base crude oil, devoid of gasoline or kerosene. Distillation tests show 17.9% gas oil. The rest consists of heavy lubricating oil and petroleum residue.

Analysis by Canadian Oil Co., Petrolia, Ontario, is as follows:

	per cent.	sp. gr.	A. P. I.	Viscosity @ 100° F.
Light gasoline ..	nil			
Total gasoline or naphta ..	nil			
Kerosene	nil			
Gas oil	17.9	0.902	25.4	
Non-viscous lubricating distillate	14.9	920-939	22.3-19.2	50-100
Viscous lubricating distillate	11.8	939-954	19.2-16.3	100-200
Residium	23.4	954-984	16.3-12.3	above 200
Medium lubricating distillate	31.6	1.010	8.6	
Distillation loss	4.	—	—	—

The gas has calorific value of 898 B.T.U.

GAS ANALYSES, LAKES ENTRANCE:

	A %	B %	C %	D %	E %	F %	G %
Carbon dioxide	—	0.2	0.19	1.6	2.19	1.80	0.82
Unsaturated hydro-carbon ..	—	—	0.05	—	—	—	—
Oxygen ..	11.8	—	0.90	1.2	0.4	0.20	1.96
Carbon monoxide ..	—	—	—	—	—	—	—
Methane	44.2	81.25	93.74	26.1	94.21	56.45	78.54
Ethane	—	—	—	—	—	—	—
Hydrogen	—	—	—	—	—	—	—
Nitrogen	44.0	18.55	5.12	71.1	3.2	41.55	18.68
Hydrogen sulphide	—	—	—	—	—	—	—
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Gross calorific value calculated per cubic foot ..	—	865	998	278	1003	601.2	836
Calculated specific gravity	—	—	—	—	585	—	—

A = No. 1	L.E.D. Co.	Lab. No. 1924/503
B = No. 1	L.E.D. Co.	Lab. No. 1924/524
C = No. 1	L.E.D. Co.	Lab. No. 1924/544
D = No. 2	L.E.D. Co.	Lab. No. 1928/627
E = No. 1	Point Addis Co.	Lab. No. 1929/1032
F = No. 1	Kalimna Oil Co.	Lab. No. 1930/138
G = No. 8	Parish of Colquhoun	Lab. No. 1941/94

2. WOODSIDE OIL

From the scanty data at present available, this oil appears to be probably of mixed (paraffinic-asphaltic) base origin. It otherwise resembles greatly the Lakes Entrance oil in that it lacks the gasoline and kerosene fractions.

Its specific gravity is: S. G. 0.92 to 0.93.

Its colour is dark brown like the Lakes Entrance oil and its smell appears to be very close indeed to the very peculiar smell of the latter oil.

NOTE ADDED WHILE GOING TO PRESS

Since the above was written, Woodside No. 2 Well still drilling at 6069 feet, has made news by striking several oil shows in sandstones below a massive 800 feet capping of plant-bearing Jurassic shale. Probably situated not very far above the base of the Jurassic, these shows appeared below 5100 feet and again lower down, especially below 5600 feet.

Although materially different from the oil discovered by the same well in the Tertiary, this oil does appear to bear some relationship to it. However, certain lighter fractions absent in the Tertiary oil, may be present here.

The immediate commercial importance of this discovery is probably not great; but in the broader evaluation of Australian oil exploration, its importance can hardly be exaggerated. It does appear to indicate that some guiding principles of Victorian oil exploration, expressed in this and earlier papers, may be substantially correct.

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NOUVELLE-CALÉDONIE

(NUEVA CALEDONIA)

NOTE SUR LES GISEMENTS DE GAZ ET DE PÉTROLE DE NOUVELLE-CALÉDONIE

Par le SERVICE DES MINES DE NOUVELLE-CALÉDONIE

RESUMÉ

Les recherches d'hydrocarbures viennent à peine de commencer en Nouvelle-Calédonie et il n'est pas encore possible de conclure à l'existence ou à la non existence de gisements de gaz ou de pétrole. Cette courte étude ne traitera donc que des indices connus et des travaux effectués à ce jour.

A—ELÉMENTS DE GÉOLOGIE

Le sous-sol de la Nouvelle-Calédonie comprend trois grandes formations:

les terrains métamorphiques—Ils constituent la majeure partie du Nord de l'Ile, et forment une chaîne fortement plissée comprenant des séricitoschistes et des chloritoschistes ainsi que quelques micaschistes et des chloritoschistes ainsi que quelques micaschistes et gneiss.

les terrains sédimentaires—Allongés du Nord au Sud le long de la côte occidentale de l'Ile, ils se composent de grès, de grauwackes, de phtanites, de schistes et de calcaires; ils s'étagent du Permien au Miocène.

les terrains ignés et volcaniques—Un vaste ensemble de péridotites et serpentines occupe la Sud de l'Ile, à l'exception d'une mince bande côtière; il forme également quelques importants massifs à fort relief alignés le long de la côte Ouest.

Des épanchements basalto-andésitiques (Paléogène) s'étendent largement dans la moitié Nord du Territoire entre Koumac et Bourail.

La tectonique de l'Ile est extrêmement complexe: d'après M. Piroutet (1917) on peut considérer la Nouvelle-Calédonie "comme une chaîne constitués de plis serrés disposés en éventail avec déversement au S. W. sur la côte Ouest, au N. E. sur la côte Est"; les zones calmes sont relativement rares.

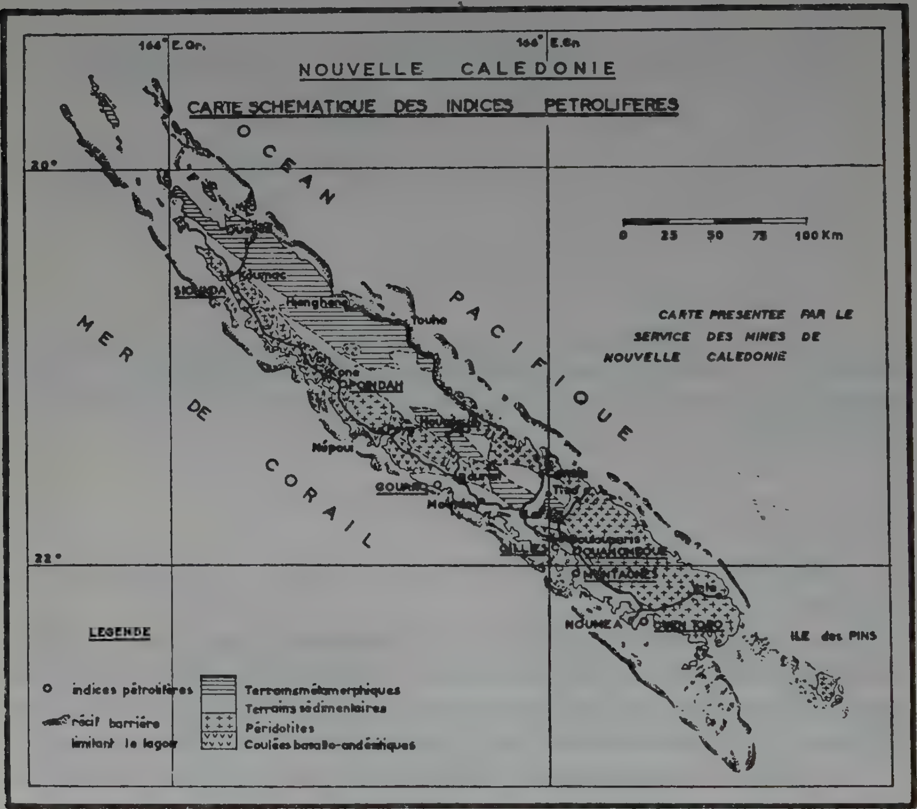

Figure 1.

Sur la côte occidentale, approximativement au centre de l'Ile, se trouve un seuil important, appelé "Seuil de Moindou" (Y. Jullian, 1955) sur lequel sont venues mourir les mers Crétacées et Tertiaires. Ce seuil a joué un rôle important dans la paléogéographie de l'île, il partage l'île en deux secteurs:

Au Nord de ce seuil la majeure partie des terrains sédimentaires à l'exception des environs de Gouaro, est fortement tectonisée;

Au Sud au contraire, la zone sédimentaire tectonisée occupe une place plus restreinte.

Les formations sédimentaires plissées sont représentées par la "formation des grauwackes" (Permo-Jurassique) et plus particulièrement par la "formation à charbon" (Jurassique supérieur-Crétacé), formation très plastique comprenant essentiellement des argiles fines, schisteuses, et quelques lentilles de grès, et par la "formation des phtanites" (Eocène inférieur) comprenant des jaspes noirs, des lentilles calcaires, des conglomérats et des brèches.

Les formations sédimentaires calmes sont représentées par le faciès "flysch", schisto-calcaire, de l'Eocène supérieur et une "série fluvio-marine", argilo-sableuse, mollassique appartenant au Néogène qui n'affleure que dans la région de Népoui.

Une récente mission géologique effectuée par Y. Jullian et le Dr. Trumpy (1955) a attiré l'attention sur l'extension probable des formations sédimentaires au delà du littoral actuel, jusqu'au récif barrière qui entoure toute l'Ile.

B—DESCRIPTION DES PRINCIPAUX INDICES

Indice de Siounda (région de Koumac)

C'est en 1896 que furent découverts les premiers indices pétrolifères de l'Ile; il s'agissait de suintements d'huile paraffineuse formant une pellicule huileuse dans la rivière dite "de la mine d'huile" qui prend sa source dans le massif péridotique et serpentineux de Siounda, au Sud de Koumac.

Indice de Gomen (région de Gomen)

Les brèches de l'Eocène inférieur contiennent des éléments anguleux variés dont des calcaires "à odeur de pétrole" (A. Arnould, 1953).

Indice de Poindah (région de Koné)

R. Pomeyrol a signalé en 1951 un indice d'hydrocarbures gazeux sur la réserve indigène de Poindah dans le lit d'un petit affluent de la rivière Koné. "Le gaz vient très probablement de la "formation à charbon" (R. Pomeyrol, 1951, p. 278).

Indice de Gillès (région de Boulouparis)

J. O. Haas a découvert en 1932 des traces d'huile en deux points à Gillès, prés de Boulouparis, dans des calcaires bitumineux transgressifs de l'Eocène reposant sur un substratum de grauwackes triasiques.

Indice de Oua-Nomboué (région de Boulouparis)

Dans une courte note, A. Arnould (1953) signale des calcaires bitumineux et un indice liquide huileux dans des schistes noirs de la rivière Oua-Nomboué près de Boulouparis. Calcaires et schistes appartiennent à l'Eocène inférieur.

Indice de Montagnès (région de Boulouparis)

La transgression de l'Eocène moyen sur le Crétacé et l'Eocène inférieur a débuté par un conglomérat à gros éléments, surmonté par une puissante série de brèches, renfermant d'importantes lentilles de calcaires. Dans la presqu'île de Montagnés A. Arnould a découvert dans une de ces lentilles de calcaire des indices de bitume.

Indice de Ouen Toro (région de Nouméa)

Sur les pentes Nord-Ouest du Mont Toro près de Nouméa, O. Hass (1932) a recueilli des produits huileux dans des calcaires Eocènes bitumineux.

Tous ces indices se trouvent dans les terrains sédimentaires de la côte occidentale: "la formation à charbon" ou Eocène (à l'exception de l'indice de Siounda trouvé dans les péridotites mais probablement en relation avec l'Eocène qui affleure aux environs et peut-être sous les péridotites). A. Arnould (1953) a attiré l'attention sur la relation qui existe dans les bassins de Gomen et de Boulouparis "entre les indices d'hydrocarbures et leur répartition géographique, liée aux grandes lignes de transgression et aux niveaux de brèches de l'Eocène".

C—HISTORIQUE DES RECHERCHES DE PETROLE

Basin de Nouméa

Un sondage a été exécuté en 1908-1909 à Anse Vata dans la banlieue de Nouméa; Il aurait trouvé du gaz et de l'huile. On ne possède pas de renseignements sur ce sondage.

Une exploitation par carrière des calcaires bitumineux de Ouen Toro a été tentée sans succès en 1932.

Les études géologique entreprises après 1947 ont mis en évidence une zone sédimentaire calme, principalement formée d'Eocène, s'étendant sur plus de 50 kilomètres, des environs de Boulouparis à Païta-Nouméa.

Basin de Gouaro

Les études effectuées en 1953-1954 dans le Nord de l'Ile par la S.R.E.P.N.C.[1] ont découvert une structure anticlinale dans l'Eocène supérieur à Gouaro près de Bourail. Deux sondages totalisant 1.049 mètres ont été forés, tous deux sont restés dans l'Eocène supérieur. Selon R. Pomeyrol (1955) ces sondages auraient révélé l'existence d'indices hydrocarburés en profondeur.

Les études effectuées en 1955 par Y. Jullian lui ont permis de dire "qu'en tenant compte à la fois de la transgressivité de l'Eocène supérieur et des larges ondulations qui l'affectent on pouvait considérer la région de Gouaro comme un biseau régional Eocène supérieur, plissé à grand rayon de courbure, reposant directament au Sud-Ouest sur le substratum de Lias ou de Trias, constitué par les grauwackes du *seuil de Moindou.* En conséquence, il est possible d'escompter, sous la couverture d'Eocène supérieur la présence de biseaux poreux et perméables de l'Eocène inférieur ou de la *formation à charbon*".

Basin de Koumac

Des travaux en puits et galeries ont été effectués en 1896-1904 sur les principaux indices de Siounda, dans les péridotites; ils auraient récupéré quelques litres d'huile. Des sondages exécutés en 1914-1919 aux environs de l'indice principal auraient également trouvé des traces d'huile. En 1953-1954, la S.R.E.P.N.C. a implanté au pied du massif de Siounda, 4 sondage totalisant 374 mètres. Ils sont restés dans le complexe basalto-péridotique de Siounda et n'ont trouvé que des traces d'huile.

[1] S.R.E.P.N.C.—Société de Recherche et d'Exploitation de Pétrole en Nouvelle-Calédonie.

D—POSSIBILITÉS PÉTROLIFÈRES DE LA NOUVELLE-CALÉDONIE

D'importantes recherches géophysiques et des sondages profonds seront encore nécessaire avant de pouvoir tirer des conclusions quant aux possibilités pétrolifères de l'Ile; cependant les indices des environs de Nouméa et de Boulouparis et l'existence vraisemblable d'un bassin sédimentaire de dimensions notables et relativement calme dans cette zone permettent de les envisager avec un certain optimisme.

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AUSTRALIAN

(AUSTRALIA)

THE SEDIMENTARY BASINS OF THE AUSTRALIAN TERRITORY OF PAPUA AND NEW GUINEA

By N. OSBORNE [1]

ABSTRACT

Two important sedimentary basins are recognised in the Australian Territory of Papua and New Guinea, one in the north called the Northern Basin, the other in the south, called the Papuan Basin. Both extend westward into Netherlands New Guinea and are fundamentally geosynclinal structures. They are separated by a zone of crystalline basement which occupies the northern half of the central cordillera, but there seems to be some connection, at present obscure, through the saddle between the Bismarck and Owen Stanley Ranges.

The Papuan Basin contains a considerable thickness of sediments ranging from Upper Jurassic to Pliocene. The Basin sediments have been strongly folded and, in some zones, highly faulted to the point of imbrication. Gas and oil seepages, mostly small, are distributed widely throughout the basin.

The Northern Basin is made up solely of Upper Tertiary rocks, predominantly marine, resting unconformably on granitic and metamorphic basement with scattered erosional remnants of uppermost Cretaceous and Eocene limestone. The zone of greatest known aggregate thickness, reaching about 35,000 feet, occurs in front of the steep upthrust of the Bewani-Torricelli Mountains and is also the zone of strongest folding and faulting. Gas and oil shows are relatively scarce, but widely distributed.

INTRODUCTION

Commercial oil accumulations have not yet been found in Papua and New Guinea, but the presence of oil and gas seepages and large areas of unaltered sedimentary rocks has led to considerable exploration and some drilling, especially following liberalisation of the petroleum prospecting ordinances in 1936. Prior to this date only a very limited amount of geological exploration had been carried out and even

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now, while much of the western part of the territory has been closely examined, areas in the east and in the central highlands remain very little known.

The following account therefore deals entirely with the western part of the Australian Territory. The information comes mainly from the Australasian Petroleum and Island Exploration Companies, in which Standard-Vacuum Oil Co., New York; British Petroleum Company Limited, London; and Oil Search Ltd., Australia, are partners.

DISTRIBUTION OF SEDIMENTARY BASINS

Two major sedimentary basins are recognised in the Australian Territory. These are separated by the central cordillera, the high and rugged backbone of the island of New Guinea, whose northern component is made up almost entirely of granitic and metamorphic rocks. The accompanying map shows the extent of these basins and the localities referred to later in this article.

The Papuan Basin, the larger and better known, lies along the south flank of the central cordillera mainly in west Papua. It continues westward into Netherlands New Guinea and pluges south-eastward beneath the Papuan Gulf. The narrow fringe of Tertiary strata outcropping along the coast of the eastern "tail" of the island of New Guinea probably indicates extension beneath the Coral Sea.

The Northern Basin also extends into Netherlands New Guinea, north of the central cordillera, and continues southeastward mostly north and northeast of the Sepik, Ramu and Markham Rivers, to disappear beneath the Huon Gulf. Upper Tertiary strata outcropping on the island of New Britain might indicate eastward extension into the Bismarck Archipelago, but not much is known of this complicated area.

THE PAPUAN BASIN

Stratigraphy

The oldest unmetamorphosed sedimentary rocks so far recognised in the Australian territory are Permian limestones which rest unconformably on granite in the Kubor Range of the central mountains. These and even older Palaeozoic sediments might be present in the de-


N.Osborne - "Sedimentary Basins In Papua and New Guinea."
BISMARCK ARCHIPELAGO
NEW IRELAND
NEW BRITAIN
OENAKE SERRA
Bewani Geosyncline
BEWANI TORRICELLI
PRINCE ALEXANDER
NORTHERN BASIN
ADELBERT
Madang Basin
FINISTERRE SARUWAGED
CENTRAL MOUNTAINS
BISMARCK RANGE
PAPUAN BASIN
HUON GULF
ALBERT MTS
OMATI 2
OMATI 1.
ARAMIA
WANA
KARIAVA
UPOIA
1 & 2
GULF OF PAPUA
OROI
PORT MORESBY
OWEN STANLEY RANGE
0
100
200
300
400
500
MILES
AUSTRALIAN TERRITORY
of
PAPUA & NEW GUINEA
SHOWING
MAIN SEDIMENTARY BASINS
PAPUAN BASIN
DEEP EXPLORATION WELLS
OMATI
SCALE:- 1:6,336,000 or 1 100 miles

P.M. 1955/307

eper parts of the Papuan Basin, but the section must be made up essentially of rocks ranging in age upward from the Jurassic.

The entire stratigraphic sequence from lower Upper Jurassic to Pliocene and Pleistocene is represented somewhere or other in the Basin, but big gaps occur locally due to periodic diastrophism and associated west to south west migration of the geosynclinal axis. Despite the important disconformities, however, appreciable angular unconformities are conspicuously absent in the areas examined. The aggregate maximum thickness is considerable.

The Mesozoic has its greatest development in the central highlands where a section of geosynclinal facies and thickness appears to end abruptly against a great regional fault which brings up granite and metamorphic basement to form the northern half of the cordillera. The Upper Jurassic consists almost entirely of dark silty shales, 6,000 feet thick, with a massive coralline limestone 200 feet thick lying 800 feet above the base. The conformably overlying Cretaceous is 18,000 feet thick with the whole sequence apparently represented except the uppermost part. The Lower Cretaceous, 6,000 feet, consists of well bedded volcanic breccias, tuffs, conglomerates, greywackes, siltstones and shales, the Upper Cretaceous, 12,000 feet, of shales, greywackes and tuffaceous mudstones.

Towards the west and southwest the section becomes thinner and the greywackes less prominent. In the Upper Fly River area the Jurassic comprises over 4,000 feet of conglomerates, sandstones and silty shales, the conglomerates being made up almost completely of granite, quartz and felspar and the sandstones of quartz. The Cretaceous is 3,500 feet thick, mostly mudstone (or massive shale) with some thick glauconitic quartz sandstone members, especially at the base.

Oil and gas seepages have been reported from several localities along the southern foothills.

Lower Tertiary rocks are widely distributed throughout the central mountains and southern foothills. West of the Albert Mountains and the Bismarck Range they are represented by relatively thin limestone sections generally less than 2,000 feet— belonging to some part or other of the Eocene and Oligocene sequence. At the southeast end of the Albert Mountains and in the Port Moresby district, the Eocene is dominantly siliceous. Near Port Moresby Eocene cherty shales and marls with some polyzoal sandstones, foraminiferal limestones and

tuffs, totalling about 5,000 feet are overlain by more than 2,000 feet of Oligocene tuffs and agglomerates with subordinate shale and limestone.

The *Upper Tertiary* sediments represent a second phase of intense geosynclinal development. The strata of the lower Miocene Aure Trough, as now exposed in the Albert Mountains, comprise over 20,000 feet of greywackes and mudstones, with tuffs, agglomerates, lava flows and limestones at the base. These grade westward into a thinner but still substantial section of limestones on the shelf area of west Papua. Limestones become important also east and southeast of the Albert Mountains.

On the western flank and southeastern plunge of the Albert Mountains the lower Miocene strata are overlain by a maximum of 6,000-8,000 feet of upper Miocene calcareous mudstones and quartz sandstones. These also thin out towards the west.

The Pliocene reaches thicknesses of 6,000-8,000 feet in several areas along the margin of the foothills. The section is generally dominantly arenaceous, chiefly quartz sandstones, with conglomerates containing abundant volcanic pebbles often prominent at the base. The lower part is marine and grades upwards into non-marine sandstones and mudstones with lignitic beds and coal bands.

Pleistocene is represented by tuffs, agglomerates, lava-flows and flat-lying redeposited erosion products from the numerous now-extinct volcanoes scattered through western Papua.

Oil and gas seepages, mostly small, are common in and near the zone of the Aure Trough, coming from both lower and upper Miocene sediments.

Structure

The regional trend throughout most of the exposed part of the Papuan Basin is northwest to west northwest, but the folded Albert Mountains representing the Aure Trough, strike more nearly north. The folds of the Aure Trough are characteristically long, narrow and steeply dipping, often crest faulted and becoming asymmetric, and sometimes diapiric, along the western foot of the Albert Mountains. The synclines broaden as the structure swings into the prevailing regional northwest to west northwest strike, both in the foothills to the north

and along the coast in the south, but the anticlines remain strongly folded.

The central mountains and the western foothills which comprise the greater part of the exposed basin sediments, can be divided roughly into three structural zones:

1. Mountain zone of open folding in which the individual folds structures are of great length and amplitude.
2. Mountain foothills zone of sharp folding and faulting, in places imbricate.
3. Outer foothills zone of strong folding, mostly unfaulted, the individual structures being generally long and fairly steeply dipping but of smaller amplitude than the mountain folds.

The great regional fault which appears to terminate the basin in the north also strikes generally northwest to west northwest, but the central mountains have been very sparsely explored and not much is known about it. It is thought to be a high angle thrust. There is some major faulting along the southern margin of the foothills also, particularly in the region of the Aure Trough. These might be sheer thrusts.

NORTHERN BASIN

Stratigraphy

Mesozoic strata are almost entirely absent north of the central cordillera and the oldest sedimentary rocks found in the northern Basin are uppermost Cretaceous and Lower Tertiary limestones scattered through the western areas as erosional remnants between Miocene deposits and crystalline basement. The basin is essentially geosynclinal but consists of at least two units, the Bewani Geosyncline and the Madang Basin, whose relation to each other is not at all clear.

The Bewani Geosyncline extending from across the Netherlands New Guinea border eastward to plunge beneath the ocean near the mouth of the Sepik River is the better known. It appears to have been a very active structure of short duration; an aggregate of about 35,000 feet of strata, resulting from a depositional period confined to the Miocene and Pliocene, having been subsequently folded, faulted, uplifted and eroded.

The greatest thickness occurs immediately to the north of the Bewani and Torricelli Mountains which have been upfaulted and eroded

to expose granitic and metamorphic basement. There the basal Miocene is largely volcanic; tuffs, agglomerates and lava flows with interbedded limestones, greywackes and mudstones. Volcanics persist throughout the Miocene but diminish upwards while calcareous sediments and sandstones increase. The total Miocene thickness is 16,000-20,000 feet, the uppermost 1,000-4,000 feet being mainly globigerina marl and limestone with minor volcanic interbeddings.

The Pliocene section is also very thick in this zone, totalling 12,000-17,000 feet. The lower half consists chiefly of marine mudstones and sandstones, the upper is non-marine, mainly conglomerates, sandstones and mudstones with some coal seams.

South of the Bewani-Torricelli Mountains, the volcanic element rapidly diminishes and the section thins steadily towards the Sepik River, with younger shelf deposits overlapping progressively on to basement. In the Oenake-Serra Hills the upper Tertiary section is generally thin, incomplete and mainly calcareous.

The Miocene section in the Madang Basin is similar in lithology and thickness to that in the Bewani Geosyncline, but the Pliocene is thinner.

Only one oil seepage has been proved in the Northern Basin, at Matapau on the coast east of Wewak, but several gas seepages and a few occurrences of oil odors in outcrops are known from widely scattered areas in the Bewani and Madang sections.

Structure

The regional trend in the Northern Basin, as in the Papuan, is north-west to west northwest. The Bewani, Torricelli and Prince Alexander Mountains, arranged slightly on echelon, rise steeply in the north along a zone of high angle thrust faults and slope more gently southwest towards the Sepik River. A zone of sharp and narrow folds, some faulted, lies along the foot of the frontal scarp, and the deeply eroded remains of similar structures occur in the mountains themselves. South of the mountains the folds are broader and more gentle, with a swing in strike towards the north in some areas.

The Oenake and Serra-Hills appear to be broad regional basement uplifts of anticlinal form eroded to expose the core of crystalline rocks.

The regional structure in the Madang Basin is rather obscure. The Finisterre-Saruwaged Range appears to be a basement uplift of the

Serra Hills type and the Adalbert Mountains too might comprise this type of structure although they lie along the extension of the Bewani-Prince Alexander trend. In any case the individual structures between these mountains and the Bismarck Range are strongly folded.

EXPLORATION DRILLING

Exploration drilling in recent years has been confined to the Papuan Basin where 9 deep wells have been completed since 1946. The deepest of 5 drilled in the zone of the Aure Trough was Kariava 12,621 feet, and of the 4 drilled in the shelfward area, Omati No. 1,14,352 feet. The only well to penetrate the entire sedimentary section was Aramia which reached granite basement at 6,600 feet and was abandoned, after testing, at 6,628 feet.

Traces only of oil, small volumes of wet gas and variable amounts of salt water were obtained from all of these tests.

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INDICE DE AUTORES DEL TOMO II

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